Retrospective Length-Based Analysis of Bristol Bay Red King Crabs: Model Evaluation and Management Implications

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Abstract

A length-based model has been used to estimate stock abundance of Bristol Bay red king crabs (*Paralithodes camtschaticus*) since the model was developed in 1993. In this study, we conducted a retrospective analysis of the performance of this model for assessment and fishery management. Results from the model assessment in 2000 were used as baseline reference estimates. Retrospective and reference estimates have common trends over time, which are similar to survey estimates. Assumptions about natural mortality and indirect fishing mortality affect recruitment and abundance estimates. Due to low natural mortality and indirect fishing mortality during the 1990s, retrospective estimates tend to be biased low for mature female and large male crabs and biased high for small male crabs. Relative errors derived from differences between retrospective and reference estimates for Bristol Bay red king crabs range from –20% to 11%, much smaller than those derived from major groundfish stock assessments in the eastern Bering Sea. Stock-recruitment curves estimated in terminal years 1993-2000 generally have a similar shape. Although historical errors in stock assessments may not affect selection of the current harvest strategy, their impact on annual guideline harvest level can be substantial in some years when they trigger a shift in harvest rate because the target harvest rate is a step function of stock size.

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Introduction

Bristol Bay red king crabs (*Paralithodes camtschaticus*) support the largest king crab fishery in Alaska, with a peak catch of 59,000 t in 1980. In 1968 the National Marine Fisheries Service (NMFS) initiated a trawl survey to partially assess the stock, and an annual trawl survey covering the full stock distribution has been conducted since 1972. Abundance estimates were derived from survey data using an area-swept approach. To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, in 1993 the Alaska Department of Fish and Game developed a length-based analysis (LBA) that incorporates multiple years of data and multiple data sources in the estimation procedure. Annual abundance estimates of the Bristol Bay red king crab stock from the LBA have been used to manage the directed crab fishery and to set crab bycatch limits in the groundfish fisheries since 1995 (Fig. 1). A stock-recruitment (S-R) relationship, estimated from the results of the LBA, was used to develop the current harvest strategy. Given the critical role of the LBA in the management of one of the world's most economically valuable crab fisheries, it is prudent to evaluate its performance during its first 7 years of application.

The purpose of this study was to conduct a retrospective analysis of the performance of the LBA for stock assessment and fishery management. Specifically, we (1) compared the abundance estimates from LBA assessments conducted in terminal years 1993-1999 with those from the assessment conducted in 2000, (2) compared the S-R relationships estimated from assessments in terminal years 1993-2000, and (3) evaluated the implications of our findings to fishery management.

Methods

Male Population Model

The LBA was described in detail by Zheng et al. (1995a,b). Crab abundances by carapace length (CL) and shell condition in any one year result from abundances in the previous year minus catch and handling and natural mortalities, plus recruitment and additions to or losses from each length class due to growth:

$$\begin{aligned} N_{l+1,t+1} &= \sum_{l'=1}^{l'=l+1} \{P_{l',l+1}\ [(N_{l',t} + O_{l',t})\ e^{-M_t}\ -\ C_{l',t}\ e^{(y_t-1)M_t}]\ m_{l',t}\}\ +\ R_{l+1,t+1}\,, \\ O_{l+1,t+1} &= [(N_{l+1,t} + O_{l+1,t})\ e^{-M_t} - C_{l+1,t}\, e^{(y_t-1)\,M_t}]\ (1 - m_{l+1,t})\,, \end{aligned} \tag{1}$$

where $N_{l,t}$ and $O_{l,t}$ are new-shell and old-shell crab abundances in length class l and year t, M_t is the instantaneous natural mortality in year t, $m_{l,t}$ is the molting probability for length class l in year t, $R_{l,t}$ is recruitment into length class l in year t, y_t is the lag in years between assessment survey and the fishery in year t, $P_{l',l}$ is the proportion of molting crabs growing

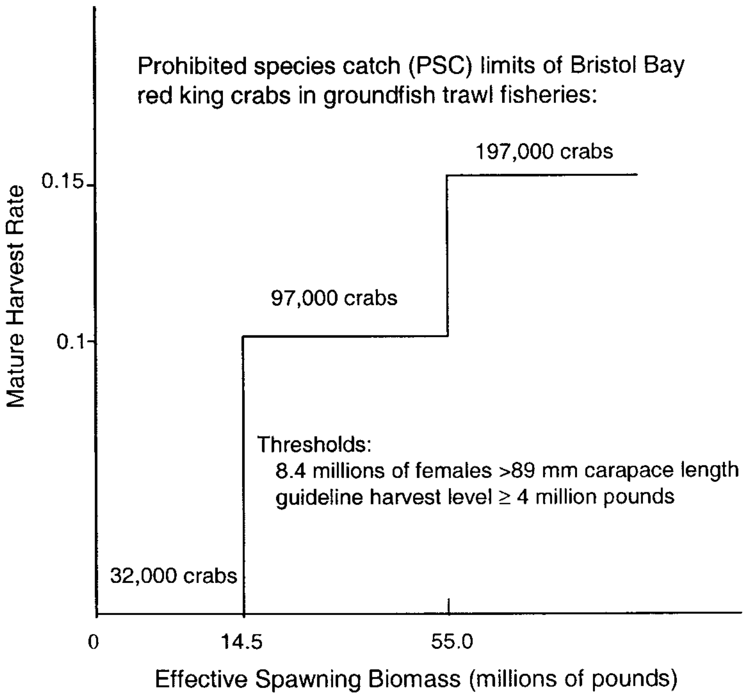

Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crabs) of Bristol Bay red king crabs in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rate is based on current-year estimates of effective spawning biomass (ESB), whereas PSC limits apply to previous-year ESB. In addition to the 14.5 million pound ESB threshold, two additional criteria must be met in order to prosecute the fishery: the abundance of large (>89 mm CL) females must equal or exceed 8.4 million crabs, and the guideline harvest level must be greater than or equal to 4 million pounds

from length class l' to l after one molt, and $C_{l,t}$ is the catch of length class l in year t. For practical purposes M_t includes indirect fishing mortality, because it could not be distinguished from M_t due to lack of data.

We set the minimum carapace length at 95 mm for males and modeled crab abundance with a length-class interval of 5 mm. The last length class included all crabs ≥169-mm CL. $P_{l',l}$, $m_{l,t}$, and $R_{l,t}$ are computed as follows.

Mean growth increment per molt is assumed to be a linear function of pre-molt length:

$$G_l = a + b\iota \tag{2}$$

where a and b are constants. Growth increment per molt is assumed to follow a gamma distribution:

$$g(x \mid \alpha_l, \beta) = x^{\alpha_l - 1} e^{-x/\beta} / [\beta^{\alpha_l}\ \Gamma(\alpha_l)]. \tag{3}$$

The expected proportion of molting individuals growing from length class l_1 to length class l_2 after one molt is equal to the sum of probabilities with length range $[\iota_1, \iota_2)$ of the receiving length class l_2 at the beginning of next year:

$$P_{l_1,l_2} = \int_{\iota_1 - \iota}^{\iota_2 - \iota} g(x \mid \alpha_l, \beta)dx \tag{4}$$

where ι is the mid-length of length class l_1. For the last length class L, $P_{L,L}$ = 1.

The molting probability for a given length class and time t is modeled by an inverse logistic function:

$$m_{l,t} = 1 - \frac{1}{1 + \alpha_t\ e^{-\beta_t \iota}} \tag{5}$$

where α_t and β_t are parameters, and ι is the mean length of length class l. Three logistic functions were used to describe the molting probability during different periods (Zheng et al. 1995a): high molting probabilities with α_1 and β_1 during 1972-1979; low molting probabilities with α_2 and β_2 during 1980-1984, 1992-1995, and 1999-2000; and intermediate molting probabilities with α_3 and β_3 during 1985-1991 and 1996-1998.

Recruitment is defined as recruitment to the model and survey gear rather than recruitment to the fishery. Recruitment is separated into a time-dependent variable, R_t, and size-dependent variables, U_l, representing the proportion of recruits belonging to each length class. We assumed that R_t consists of crabs at the recruiting age with different lengths and thus represents year-class strength for year t. $R_{l,t}$ is computed as

$$R_{l,t} = R_t U_l \tag{6}$$

where U_l is described by a gamma distribution similar to equations 3 and 4 with a set of parameters α_r and β_r.

Female Population Model

The LBA for female crabs is the same as the male crab model except that catch equals zero and molting probability equals 1.0 to reflect annual molting (Powell 1967). We set the minimum carapace length at 90 mm for females, and the last length class included all crabs ≥140-mm CL.

Data

Landings of Bristol Bay red king crabs by length and year were obtained from annual reports of the International North Pacific Fisheries Commission from 1972 to 1973 and from the Alaska Department of Fish and Game from 1974 to 1999. Tow-by-tow trawl survey data for Bristol Bay red king crabs during 1975-2000 were provided by NMFS.

We estimated abundances by sex, carapace length, and shell condition using the "area-swept" method without post-stratification. If multiple tows were made for a single station in a given year, the average of the abundances from all tows was used as the estimate of abundance for that station. The survey catch from station F06 in 1991 was discarded because it was considered an outlier (Stevens et al. 1991).

For 1968-1970 and 1972-1974, abundance estimates were obtained from NMFS directly because the original survey data by tow are not currently available. There were spring and fall surveys in 1968 and 1969. The average of estimated abundances from spring and fall surveys was used for these 2 years. The abundance in 1971 was derived as the average of those in 1970 and 1972 because a complete survey was not conducted in 1971. We considered abundance estimates from the 1973-2000 data to be estimates of absolute abundance; before 1973 estimates were considered as relative abundance because of an apparent change in survey catchability thereafter (Zheng et al. 1995a).

The length-based population model was fitted to the abundance data after 1971 because shell condition data were limited to this time series. Eight LBA fits were conducted corresponding to terminal years of 1993-2000. The catchability for the survey gear in 1972 was estimated by the model. We assumed that the catchability for the survey gears in 1968-1971 was the same as in 1972 because the survey gears and methods were identical during these years (Reeves et al. 1977). Thus, the relative abundances from 1968 to 1971 were divided by the estimated catchability in 1972 to obtain the absolute abundances. The absolute abundances from 1968 to 1993-2000 were used to construct S-R relationships.

Parameter Estimation

Mean growth increment per molt was estimated for male crabs by Weber and Miyahara (1962) and derived for female crabs from the data presented in Gray (1963). The intercept and slope parameters for the linear relationships between mean increment per molt and premolt carapace length (in millimeters) are 13.14 and 0.018 for male crabs and 16.49 and –0.097 for female crabs. Once mature, the growth increment per molt for male crabs increases slightly and annual molting probability decreases, whereas the growth increment for female crabs decreases dramatically but annual molting probability remains constant at 1.0 (Powell 1967).

Measurement errors were assumed to be lognormally distributed, and parameters of the model were estimated using a nonlinear least squares approach, which minimized the residual sum of squares (*RSS*), or measurement errors:

$$RSS = \sum_{l,t}\{[\ln(N_{l,t}+\kappa)-\ln(\tilde{N}_{l,t}+\kappa)]^2 + [\ln(O_{l,t}+\kappa)-\ln(\tilde{O}_{l,t}+\kappa)]^2\} \tag{7}$$

where $\tilde{N}_{l,t}$ and $\tilde{O}_{l,t}$ are area-swept estimates of abundances of new-shell and old-shell crabs in length class l and year t from trawl survey data, and κ is a constant set equal to 0.1 million crabs (<0.7% and 0.3% of the largest observed male and female abundances by length). Constant κ was used to prevent taking the logarithm of zero and to reduce the effect of length classes with zero or very low abundances on parameter estimation. A smaller κ gives a heavier weight for low abundances, and vice versa.

The following model parameters were estimated separately for male and female crabs: recruits for each year (year-class strength R_t for t = 1973 to 1993-2000), total abundance in the first year (1972), parameters β and β_r, and instantaneous natural mortality M_t. Molting probability parameters α_1, α_2, α_3, β_1, β_2, and β_3 were also estimated for male crabs. M_t was assumed to be a function of time and body size in the assessment with the terminal year of 1993 (Zheng et al. 1995a). To reduce the number of parameters to be estimated, M_t was assumed to be independent of body size in the assessments with terminal years 1994-2000. There were three levels of M_t for females and two levels for males in the assessments with terminal years 1994-1997 and four levels of M_t for females and three levels for males in the assessments with terminal years 1998-2000. These levels were determined interactively by searching for the best fit of area-swept estimates of abundances to the population model.

To increase the efficiency of the parameter-estimation algorithm, we assumed that the relative frequencies of length and shell classes from the first survey year (1972) approximate the true relative frequencies within sexes. Thus, we had to estimate only total abundances of males and females for the first year; 3n unknown parameters, where n is the number of length-classes, for the abundances in the first year were reduced to 2 under this assumption.

S-R Models

The results from the LBA were used to estimate the parameters of S-R models. We followed Zheng et al. (1995a) to estimate effective spawning biomass for Bristol Bay red king crabs. Male reproductive potential is defined as the mature male abundance by carapace length multiplied by the maximum number of females with which a male of a particular length can mate (Zheng et al. 1995a). If mature female abundance was less than male reproductive potential, then mature female abundance was used as female spawning abundance. Otherwise, female spawning abundance was set equal to the male reproductive potential. The female spawning abundance was converted to biomass, defined as the effective spawning biomass SP_t, using a length-weight relationship ($W = 0.02286\ L^{2.234}$, where W is weight in grams and L is CL in millimeters) (B. Stevens, NMFS, Kodiak, Alaska, pers. comm.).

The S-R relationships of Bristol Bay red king crabs were modeled using a general Ricker curve:

$$R_t = SP_{t-k}^{r1} e^{r2 - r3\ SP_{t-k} + \nu_t} \tag{8}$$

and an autocorrelated Ricker curve:

$$R_t = SP_{t-k} e^{r2 - r3\ SP_{t-k} + \upsilon_t} \tag{9}$$

where $\upsilon_t = \delta_t + a1\ \upsilon_{t-1}$, ν_t and δ_t are environmental noises assumed to follow a normal distribution $N(0,\sigma^2)$, and $r1$, $r2$, $r3$, and $a1$ are constants. Equation 8 was linearized as

$$\ln(R_t) = r2 + r1\ \ln(SP_{t-k}) - r3\, SP_{t-k} + \nu_t \tag{10}$$

and equation 9 as

$$\ln(R_t / SP_{t-k}) = r2 - r3\ SP_{t-k} + \upsilon_t . \tag{11}$$

An ordinary linear regression was applied to equation 10 to estimate model parameters $r1$, $r2$ and $r3$, and an autocorrelation regression (procedure AUTOREG, SAS Institute Inc. 1988) with a maximum likelihood method was used to estimate parameters $r2$, $r3$, and $a1$ for equation 11.

Results and Discussion

Population Abundance

The long-term trends of abundance estimates made by LBA assessments in terminal years 1993-2000 were similar (Figs. 2 and 3). Abundance increased sharply from the early 1970s to the late 1970s and then dropped dramatically during the early 1980s. Abundance fluctuated around a low

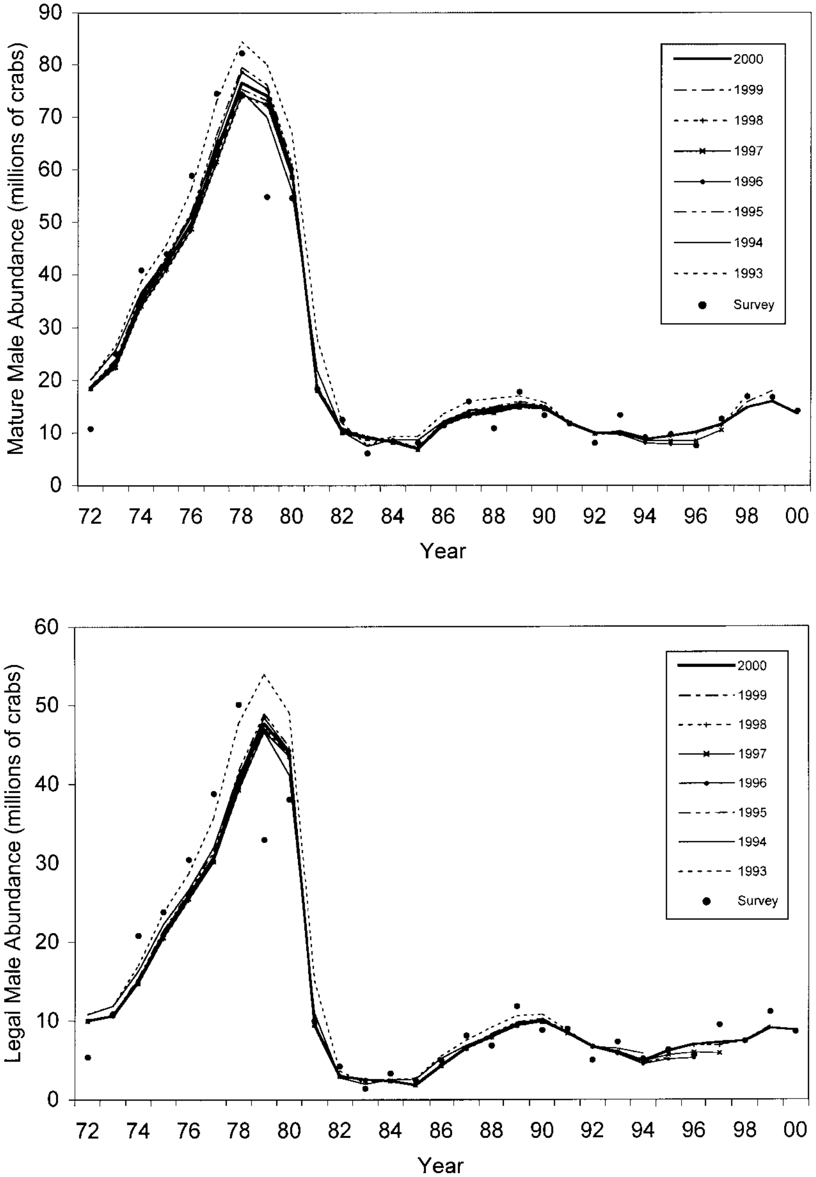

Figure 2. Comparison of mature (top) and legal (bottom) male abundance estimates of Bristol Bay red king crabs from 1972 to 2000 made by LBA assessments with terminal years 1993-2000 and by area-swept methods. Legend shows the year in which the assessment was conducted. For each assessment year, abundances were estimated from 1972 to the terminal year.

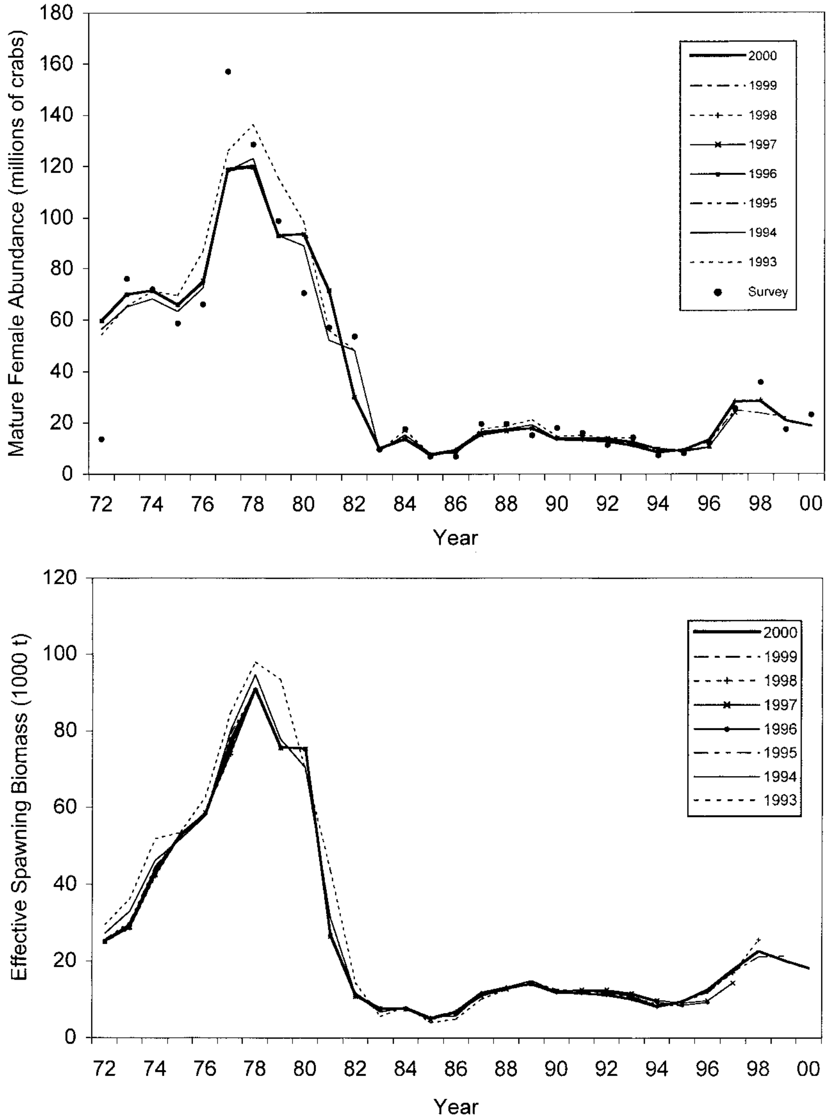

Figure 3. Comparison of mature female abundance estimates (top) and effective spawning biomass estimates (bottom) of Bristol Bay red king crabs from 1972 to 2000 made by LBA assessments with terminal years 1993-2000 and by area-swept methods. Legend shows the year in which the assessment was conducted. For each assessment year, abundances were estimated from 1972 to the terminal year.

level during the last two decades. For most years abundance estimates made in the terminal year of 1993 were slightly higher than those made in terminal years 1994-2000; this may be attributed to different assumptions about natural mortality. The LBA used in 1993 estimated natural mortality by time period and length (Zheng et al. 1995a) whereas natural mortality was assumed to be independent of length for the model used after 1993 (Zheng et al. 1995b) to reduce the number of parameters to be estimated.

The baseline estimates and the estimates made during 1993-1999 for terminal years differed. The biggest difference for total abundance occurred in 1996 with a –20% relative error (Fig. 4). In addition to the survey measurement errors, this difference may also be due to assumptions about natural mortality (i.e., process errors). Natural mortality from 1985 to 1997 was assumed constant for the stock assessments conducted before 1998 (Zheng et al. 1997a). Consistently lower model estimates than area-swept estimates of large-sized crab abundance from 1995 to 1997 (Figs. 2 and 3) prompted re-evaluation of the assumption of natural mortality. In the 1998 and 1999 assessments, we estimated a new level of natural mortality after 1993, which was much lower than estimated natural mortalities from 1972 to 1993 (Zheng et al. 1998, Zheng and Kruse 1999). The fishery was closed in 1994 and 1995, and red king crab bycatch in the groundfish fisheries was further reduced because of the depressed crab stock. Both factors may have lowered indirect fishing mortality, part of the natural mortality in the model. Overestimates of 1994-1997 natural mortality during the assessments in terminal years 1995-1997 partially caused underestimates of large-sized crab abundance in those terminal years.

Relative errors for Bristol Bay red king crab stock estimates are smaller than those for many groundfish stock estimates. Eastern Bering Sea walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), and yellowfin sole (*Pleuronectes asper*) are the three most commercially important groundfish stocks for which intensive modeling efforts have been applied, and they are enumerated by the same survey as Bristol Bay red king crabs (NPFMC 1993-2000). Relative errors range from –20% to 11% for total crab abundance, whereas relative errors of biomass range from –35% to –6% for the walleye pollock stock, from –57% to –6% for the Pacific cod stock, and from –7% to 27% for the yellowfin sole stock during the same period (Fig. 4). The smaller relative errors may be partially due to our assumed survey catchability of 1 for mature crabs, whereas groundfish models usually estimate the survey catchability. Some groundfishes, especially walleye pollock, are partly distributed in the upper water column and therefore are not fully enumerated by the bottom trawl survey. Thus, the survey catchability of the bottom trawl is usually less than 1 for many groundfish stocks. Another difference is the modeling approach: groundfish stocks are modeled by age-structure models, whereas crab stocks are analyzed by a length-based model. Availability of age information facilitates the stock assessment for groundfish stocks, but aging errors,

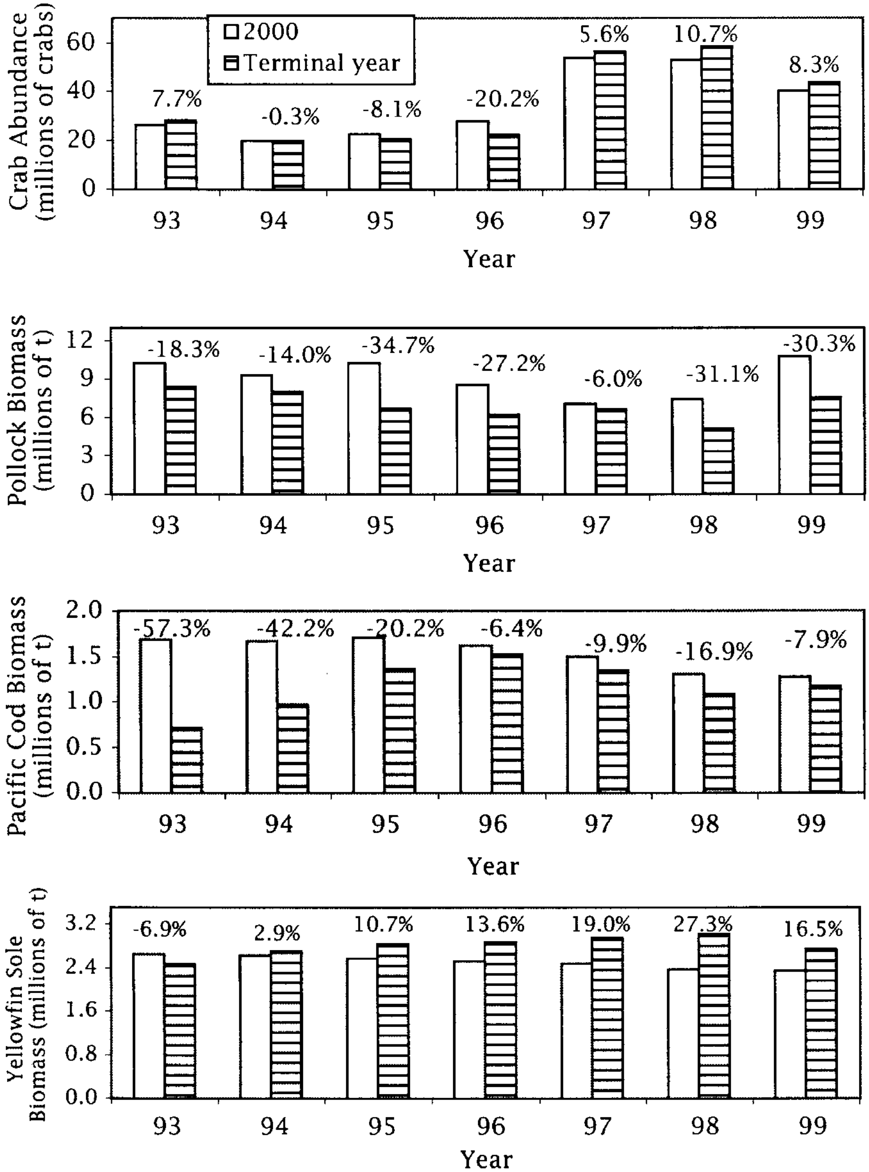

Figure 4. Comparison of historical population estimates and percent errors of the length-based model for Bristol Bay red king crabs (males >94 mm CL and females >89 mm CL) and model assessments for eastern Bering Sea walleye pollock (>age 2), Pacific cod (>age 2), and yellowfin sole (>age 1). Numbers are estimated relative errors. Data for eastern Bering Sea groundfish stocks were obtained from NPFMC (1993-2000).

especially for a long-lived species such as Pacific cod, can negatively impact the accuracy of abundance estimates. Although a length-based approach poses a greater challenge to model the animal populations than an age-based approach, length can be correctly measured and thus there are no aging errors. Also, models for many groundfish stocks were modified frequently (NPFMC 1993-2000) whereas we basically used a common model since 1994. For crab stocks, a great change in natural mortality over time further increases the complexity of stock assessments (Zheng et al. 1995a). If natural mortality is assumed constant over time as in groundfish stock assessment, an unexpected sharp drop in survey abundance will be assumed to be caused by survey measurement errors defined as the differences between true abundance and survey estimates. For crab stocks, an unexpected sharp drop can be caused by increase in natural mortality, such as occurred in the early 1980s for Bristol Bay red king crabs (Zheng et al. 1995a) and the late 1990s for St. Matthew Island blue king crabs (Zheng and Kruse 2000), changes in spatial distributions, or changes in survey catchability. If change in natural mortality over time is not modeled correctly, stock abundance can be greatly overestimated or underestimated. We suggest that a conservative management approach should be used when the stock-recruitment relationship may be depensatory or when the handling mortality rate of crab bycatch may be high (Zheng and Kruse 2002).

Historical errors in abundance estimates can be substantial for some fish stocks. In a retrospective catch-at-age analysis for Pacific halibut (*Hippoglossus stenolepis*) from 1944 to 1990, Parma (1993) indicated that historical estimates could be several times higher than the most recent estimates. As a contrast to the results by Parma (1993) that historical assessments tended to greatly overestimate Pacific halibut abundance during the 1960s and 1970s, historical assessments substantially underestimated pollock abundance in the eastern Bering Sea (NPFMC 1996). In both stocks, historical errors in abundance estimates were highly autocorrelated over time. Such large errors were most likely caused by miss-specification of survey or fishery catchabilities (Parma 1993).

S-R Relationship

We estimated S-R relationships for Bristol Bay red king crabs from the results of the LBA each year (Fig. 5). Generally, strong recruitment occurred with intermediate levels of effective spawning biomass, and very weak recruitment was associated with extremely low levels of effective spawning biomass. These features suggest a density-dependent S-R relationship. On the other hand, strong year classes occurred in the late 1960s and early 1970s, and weak year classes occurred in the 1980s and 1990s. Therefore recruitment is highly autocorrelated, so environmental factors may play an important role in recruitment success. We used the general Ricker curve to describe the density-dependent relationship and the autocorrelated Ricker curve to depict the autocorrelation effects. Because

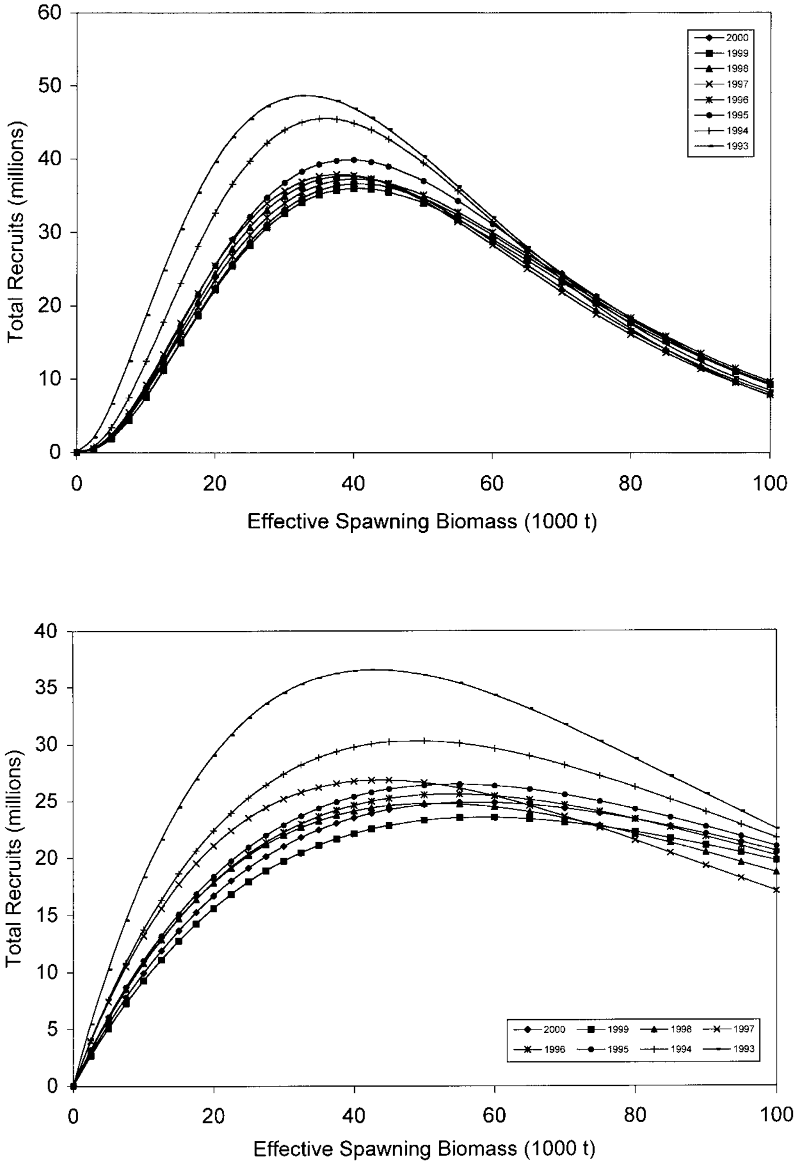

Figure 5. S-R relationships for Bristol Bay red king crabs from LBA assessments made in terminal years 1993-2000. Recruits are age 6.2 from date of hatching corresponding to a 7-year lag from spawning to recruitment. The top panel is general Ricker curves, and the bottom panel is autocorrelated Ricker curves without autocorrelated component.

the autocorrelated curve regards the strong recruitment during the late 1960s and early 1970s as a result of autocorrelation, the recruitment associated with intermediate effective spawning biomass is much lower for the autocorrelated curve than for the general curve (Fig. 5). Likewise, because the autocorrelated curve is less density-dependent, it has much higher recruitment than the general curve when effective spawning biomass is very high.

Estimated S-R relationships changed from year to year (Fig. 5). The most productive curve was estimated in 1993, which is probably the result of assumed high natural mortality for small crabs because estimated natural mortality and recruitment are confounded. The recruitment level for a given effective spawning biomass was also relatively high from the S-R curve estimated in 1994. Overall, the shapes of the S-R curves estimated in terminal years 1993-2000 are similar except for the autocorrelated curve estimated in 1997. The shape change in the autocorrelated curve estimated in 1997 was caused primarily by overestimated recruitment in the terminal year.

Management Implications

Historical errors of stock assessments affect management decisions in two ways: determination of guideline harvest levels (GHL) and selection of harvest strategies. The GHL is determined annually, and underestimates or overestimates of abundance will directly result in underestimates or overestimates of GHL each year. Harvest strategies are relatively stable and do not change annually. Once the strategies are selected, they persist for several years until new information is available to prompt a change. One approach to evaluate effects of historical errors on harvest strategies is to use the results from retrospective analyses in computer simulations to develop optimal harvest strategies or evaluate a given strategy (Parma 1993). Because of the limited scope of this study, we did not conduct computer simulations. Instead, we discussed general effects of the historical errors on optimal harvest strategies.

The most important results from the length-based model on optimal harvest strategies for Bristol Bay red king crabs are natural mortalities and S-R relationships (Zheng et al. 1997b, 1997c). Estimated natural mortalities before 1994 varied greatly from one period to another but were similar within a given period from different assessments (Fig. 6). Estimated natural mortalities after 1993 were affected by the period grouping, a process error. A fishery threshold is more favorable under the density-dependent general Ricker curve than under the weakly density-dependent autocorrelated Ricker curve. The general curve also indicates higher productivity than the autocorrelated curve and thus supports a higher optimal harvest rate. Under a given S-R relationship, increased natural mortality results in reduced optimal harvest rates. In reality, for a given data set, estimated natural mortality and recruitment from a model are usually confounded with a positive relationship. Thus, the effects of historical

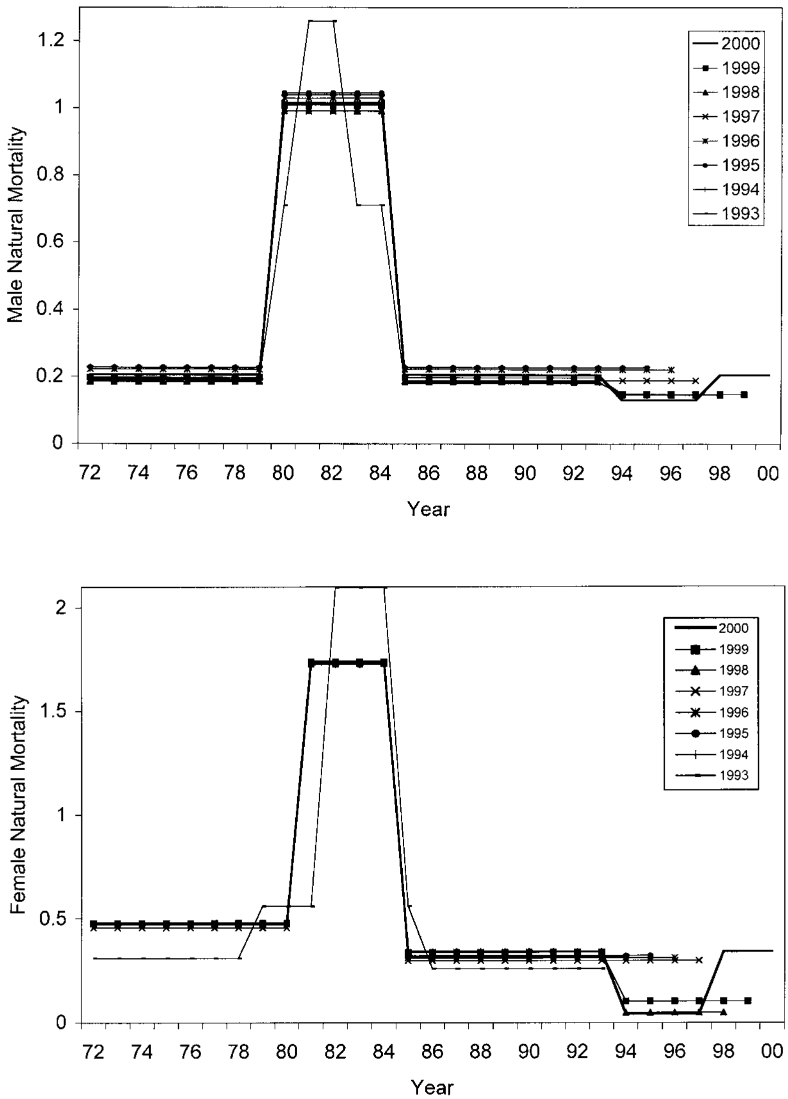

Figure 6. Estimates of natural mortalities of male (top) and female (bottom) Bristol Bay red king crabs from 1972 to 2000 made by LBA assessments with terminal years 1993-2000. Natural mortalities were assumed size-independent in the assessments with terminal years 1994-2000 and size-dependent in the assessment with the terminal year of 1993. Legend shows the year in which the assessment was conducted.

errors in estimates of natural mortality and S-R relationships may partially cancel each other.

It is unlikely that estimates of historical errors in S-R relationships will have a great impact on selecting harvest strategies. The current harvest strategy for Bristol Bay red king crabs has three components (Fig. 1): (1) step mature harvest rates based on effective spawning biomass, (2) thresholds of 8.4 millions of mature females (>89-mm CL) and GHL ≥4 million pounds, and (3) total directed catch being ≤50% of legal male crabs. The current harvest strategy was developed using the results of the LBA in 1995 through computer simulations and was adopted in 1996 (Zheng et al. 1997b, 1997c). Estimates of effective spawning biomass and shapes of S-R curves were generally similar for all assessments made in terminal years 1993-2000 (Figs. 3 and 4), so estimates of threshold levels and biomass steps for different harvest rates may not be affected much by the historical errors. The differences among years in the estimated general or autocorrelated Ricker curves were much less than the difference between the general curve and autocorrelated curve estimated in the same year. Furthermore, handling mortality rate of sublegal and female crabs caught and returned to sea is believed to be the most important parameter in determining the optimal harvest strategy (Zheng et al. 1997b). Handling mortality rate is not very well known and was not estimated in the LBA. Uncertainty on annual handling mortality rates could mask any effects of errors from the historical LBA in determining an optimal strategy.

Even though the estimated historical errors of total abundance estimates are relatively small, their impacts on annual GHL can be substantial (Table 1). In 1993, the GHL was set using the area-swept estimate, which resulted in a 30% higher mature male harvest rate than the targeted rate. Mature female abundance assessed in 1995 was close to the threshold level, and the fishery was closed due to conservation concerns. Under the current model assessment of abundance in 1995, the fishery would have been opened. The estimated mature male harvest rates are close to the targeted rates in 1996, 1997, and 1999, but are much higher in 1998. Because the step harvest rates are based on effective spawning biomass (Fig. 1), the higher estimated effective spawning biomass in 1998 resulted in a target rate of 15%. The current model assessment would have triggered a target rate of 10%. Model assessment errors could greatly affect annual GHLs if effective spawning biomass is near transition points between 0% and 10% and 10% and 15% harvest rates, as in 1995 and 1998. However, over a period of years, total GHL may not be affected much by assessment errors: total estimated GHL from 1993 to 2000 is about the same as that derived from the current model assessment.

Overall, abundance estimates by the length-based model and area-swept method had the same trends over time (Zheng et al. 1995a,b; Zheng and Kruse 2000). The model provides smoother, more consistent abundance estimates than the area-swept method, and it is considered to be an improvement over a single-year point estimate of abundance derived from

Table 1. Summary of 1993-2000 effective spawning biomass and mature male abundance estimates made in the terminal years and 2000, GHLs estimated from abundance assessments in the terminal years and 2000, actual GHLs set, and mature male harvest rates based on the actual GHLs and targeted mature male harvest rates based on the abundance assessments made in 2000.

Year	Effective spawning biomass (millions of pounds)		Mature males (millions of crabs)		GHL (millions of pounds)			Mature male harvest rate	
	2000	Terminal	2000	Terminal	2000	Terminal	Actual	Actual	Target[a]
1993	22.096	25.190	10.141	9.693	12.68	12.12	16.80	0.26	0.20
1994	17.809	18.064	8.789	9.124	0.00	0.00	0.00	0.00	0.00
1995	20.728	18.119	9.454	8.484	11.09	0.00	0.00	0.00	0.20
1996	27.485	20.263	10.181	7.795	6.48	4.96	5.00	0.08	0.10
1997	38.993	31.414	11.673	10.495	7.66	6.90	7.00	0.09	0.10
1998	49.935	56.323	14.897	17.314	9.39	16.36	16.40	0.17	0.10
1999	44.566	47.074	16.011	18.063	9.45	10.66	10.66	0.11	0.10
2000	39.936	39.936	13.663	13.663	8.35	8.35	8.35	0.10	0.10
Total	261.5	256.4	94.8	94.6	65.1	59.3	64.2		

[a]Target harvest rate was fixed at 0.2 before 1996, and from 1996 to 2000 target harvest rates were determined from Fig. 1.

GHL = guideline harvest level.

the area-swept method. The reduction of annual assessment error estimates, by the model over the area-swept method, decreases estimated errors in setting annual GHLs.

The LBA for Bristol Bay red king crabs is flexible, and we intend to continue to improve the model by incorporating new knowledge and data as they become available. One potential improvement is to include modal analysis to better address overlapping size distributions of year classes. The 1990 year class shows distinctive modes over time and provides good information for future modal analysis. Another potential improvement is to incorporate length-dependent catchability when such trawl survey data are collected and analyzed. Data on males <95 mm and females <90 mm CL could also be incorporated to reduce measurement error estimates of recruitment, particularly as new, strong year classes become recruited to the survey gear and model.

Acknowledgments

We thank three anonymous reviewers for reviewing the earlier draft of this manuscript. This report is funded in part by cooperative agreement NA97FN0129 from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. This is contribution PP-120 of the Alaska Department of Fish and Game, Commercial Fisheries Division, Juneau.

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Population Assessment Using a Length-Based Population Analysis for the Japanese Hair Crab (*Erimacrus isenbeckii*)

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Abstract

The purpose of this paper is to apply an improved length-based population analysis (LPA) to eastern Hokkaido hair crab, *Erimacrus isenbeckii*. The model incorporates stochastic growth and a gradual recruitment over length. The model contains a nonlinear least squares method to estimate growth, probability of molting, abundance, and recruitment. Abundance and catch data from 1992 to 1999 were used to test the model. The population abundances estimated by LPA fit the observed abundances well.

Estimated abundance and recruitment showed that the hair crab population in eastern Hokkaido was strongly influenced by yearly recruitment. A large abundance was the result of an abundant recruitment. This may be caused by the unsettled condition of the hair crab population in eastern Hokkaido. The estimated molt frequency by length differed from those previously reported, suggesting that some new-shelled crabs may molt. We suggest three more terms to improve the model.

Introduction

It is important to assess a stock precisely in order to manage it effectively. The purpose of this study is to apply an improved length-based population analysis (LPA) to eastern Hokkaido hair crab. The model can estimate abundances without using their ages.

Hair crab support the most important coastal fishery of Hokkaido, Japan. The area off the coast of eastern Hokkaido (from Hiroo to Kushiro) forms one of the main fishing grounds (Fig. 1). The hair crab fishery off eastern Hokkaido takes place from September to January using pots. Only male crabs that are over 79 mm in carapace length are caught and kept due to fishery restrictions. The hair crab fishery in this district has been subject to catch quota regulation since 1968 (Abe 1999). Despite such stock management, the fishery began to seriously decline in the late 1970s. In the early 1970s, the catches were about 2,000 t per year but recently the catches have been only about 500 t per year (Fig. 2). At this point the management policy for the hair crab fishery in eastern Hokkaido has failed.

The quota is based on the abundance estimated by the Kushiro Fisheries Experimental Station (KFES) pot survey in the previous year. KFES estimates the abundance roughly. First, density indices for each length are made by pot survey. Second, the indices by length are converted into indices by age. This conversion is made using a length-age relationship that was estimated by size-related changes in distribution from the pot surveys and from tagging data (Yamamoto 1966, Abe 1992) because hair crabs lack any hard structure that can be used for age determination. Using this approach it was estimated that the crabs 5 years old (80 mm in carapace length) and older molt every other year. This means that their ages do not correspond with consecutive instars. Therefore, it is difficult to apply an age-based model.

Length-based population methods have been developed since the late 1970s (Jones 1979, 1981; Fournier and Doonan 1987; Schnute 1987; Deriso and Parma 1988; Lai and Gallucci 1988; Matsuishi 1997). Sullivan et al. (1990) developed a length-based model by incorporating the growth parameters with a von Bertalanffy growth pattern and distinguishing the recruitment parameters between yearly and length components. In addition, Zheng et al. (1995) modified the length-based population model proposed by Sullivan et al. (1990) for application to the red king crab stock in Bristol Bay. The model shown by Zheng et al. (1995) incorporates a stochastic growth function in which individual crabs molt from one length class to another with stated probabilities and gradual recruitment over length.

In this study we modified the length-based population model of Zheng et al. (1995) to apply the model to the hair crab stock in eastern Hokkaido.

Methods

Data

In September and November KFES conducts a pot survey to estimate the abundance of crabs. This survey is used as a basis for the quota for the next year. The numbers of hair crabs caught per pot (CPUE) in the pot survey from 1992 to 1999 were apportioned across eight 5 mm size classes from 80 mm to 120 mm. In this classification crabs larger than 120 mm were excluded because of their rare occurrence.

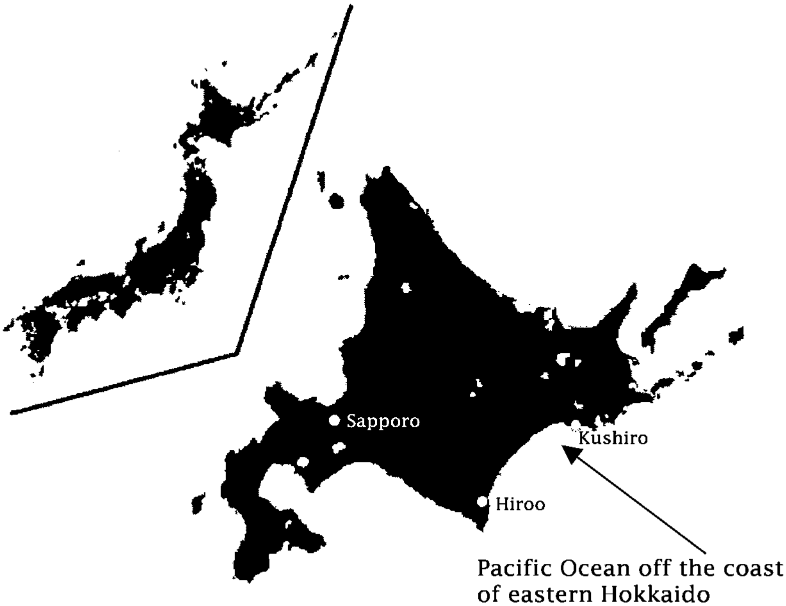

Figure 1. Fishing grounds of hair crab in eastern Hokkaido.

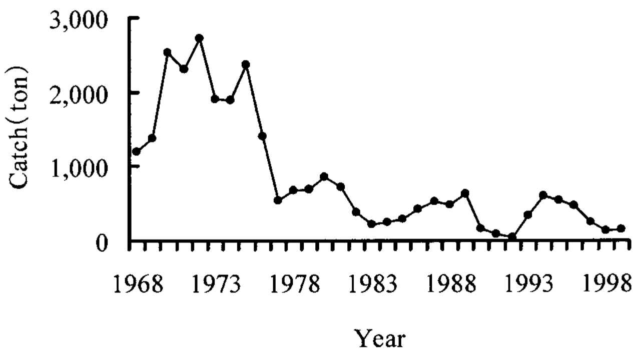

Figure 2. Trend in hair crab catches along the coast of eastern Hokkaido, 1968-1999.

The weight of landings in eastern Hokkaido of hair crabs was obtained from logbooks from 1992 to 1999. The number of crabs landed in each length class by the fishery was calculated from the CPUE in the pot survey and the weight of landings as follows. First, the proportions of numbers in each length class were calculated:

$$F_{k,n} = U_{k,n} / \sum_{I=1}^{T} U_{I,n} \tag{1}$$

where $F_{k,n}$ is the proportion of numbers in length class k in year n; $U_{k,n}$ is CPUE in length class k in year n from the pot survey; and T is the number of length classes which equals 8. The body weights of the mid-length in each class were calculated by the relationship between carapace length and body weight (Mori et al.1991):

$$W_k = 0.0056 L_k^{3.03} \tag{2}$$

where W_k is the body weight of the mid-length in length class k; and L_k is the mid-length in length class k. The proportions of weights in each length class were calculated:

$$Y_{k,n} = F_{k,n} W_k / \sum_{I=1}^{I=T} F_{I,n} W_I \tag{3}$$

where $Y_{k,n}$ is the proportion of weights in length class k in year n. $F_{k,n}$ and W_k were calculated in equations 1 and 2, respectively. In equation 4, the weights of landings in each length class were calculated:

$$H_{k,n} = V_n Y_{k,n} \tag{4}$$

where $H_{k,n}$ is the weight of landing in length class k in year n; and V_n is the total weight of the landing in year n. Finally the numbers of crabs landed in each length class were calculated:

$$C_{k,n} = H_{k,n} / W_k \tag{5}$$

where $C_{k,n}$ is the number of crabs landed in length class k in year n. The numbers of crabs landed in each length class are shown in Fig. 3.

The LPA model

Since the fishery in eastern Hokkaido starts in September, the model estimated the number of individuals in September of each year. The application of the model was limited to estimating only the abundance of legal-sized males (larger than 79 mm) because the analysis relied on the landings data.

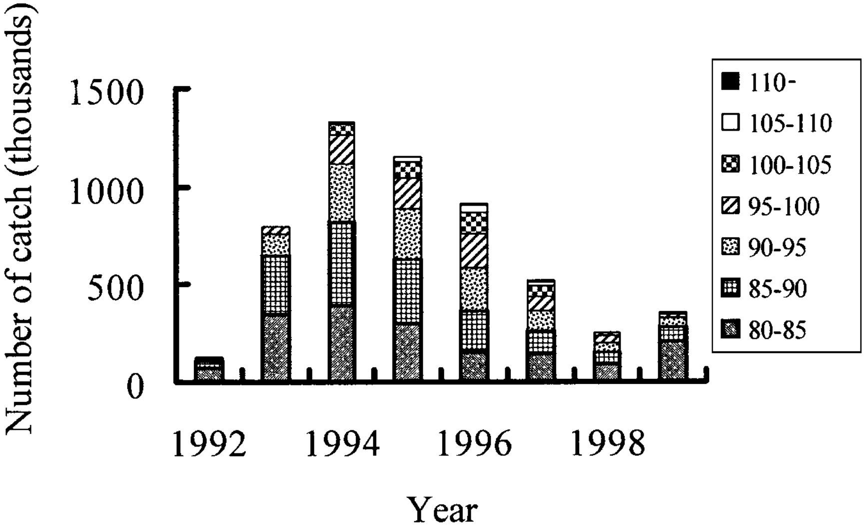

Figure 3. Estimated numbers of hair crabs in the commercial catch for each length class, 1992-1999.

The growth of individuals was expressed stochastically. The increment of carapace length per molt was estimated by using the mean carapace length in each instar proposed by Abe (1982, 1992). The increment of carapace length per molt in instar *t* was calculated:

$$\Delta L_t = L_{t+1} - L_t \qquad (6)$$

where ΔL_t is the increment of carapace length per molt in instar t; and L_t is the mean carapace length in instar t. A quadratic equation was adapted for ΔL_t in each carapace length (Fig. 4):

$$\Delta L_t = -0.0017 L_t^2 + 0.3019 L_t + 0.6154 \qquad (7)$$

The variation in growth increment per molt was described by a gamma distribution because of its versatility and flexibility in approximating several function forms (Sullivan et al. 1990):

$$g(x|\alpha_k \beta), = \frac{x^{\alpha_k - 1} e^{-x/\beta}}{\beta^{\alpha k} \Gamma(\alpha_k)} \qquad (8)$$

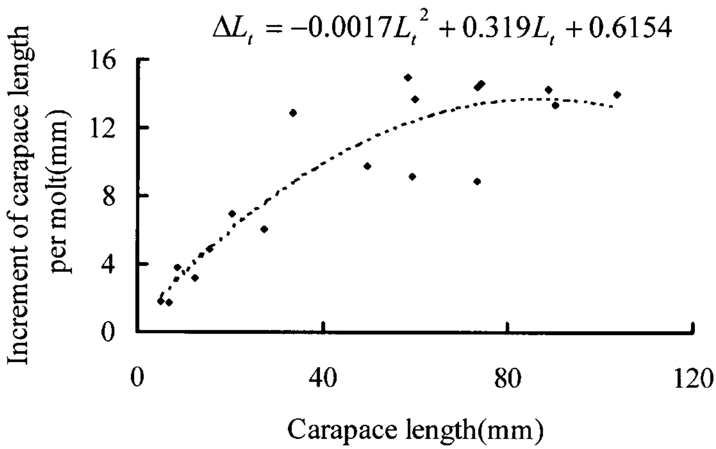

Figure 4. The relationship of carapace length increment per molt with premolt carapace length, from Abe (1982). The line shows an approximate curve.

where x is the growth increment per molt; α_k and β are parameters in gamma distribution; and Γ is a gamma function. The mean of x is given by $\alpha_k\beta$ which is equal to ΔL estimated by equation 7 in length class k. Thus $\alpha_k = \Delta L/\beta$, and the growth is represented by two parameters ΔL and β (Zheng et al. 1995). The expected proportion of crabs molting from length class i to length class k was estimated:

$$P_{i,k} = \int_{k_1-\iota}^{k_2-\iota} g(x|\alpha_i,\beta)dx \tag{9}$$

where (k_1, k_2) are the lower length and the upper length in length class k, respectively; and ι is the mid-length of length class i. In the last length class $P_{i,k} = 1$ (Zheng et al. 1995). The estimated expected proportions of each length crabs are shown in Fig. 5.

The molting probability for each length class was assumed to be dependent on length:

$$m_k = a - bk \tag{10}$$

where m_k is the molting probability of kth length class; and k is the sequential order of the length class from the smallest class of 1 to the largest size class of 8. The molting probabilities in the small crabs are higher than for the large crabs. In general, the intermolt interval increases with

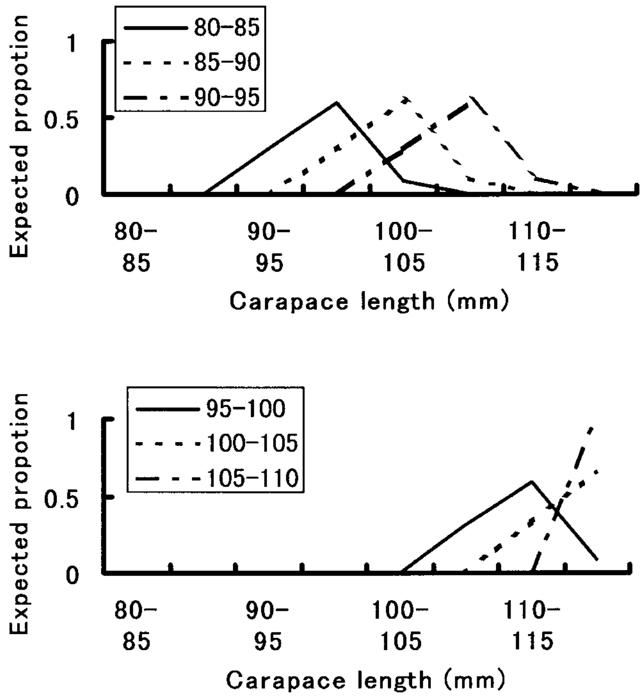

Figure 5. The expected proportion of crabs molting between sequential length classes as described by a gamma distribution.

age in brachyurans (Passano 1960). In hair crabs, small individuals molt frequently (Abe 1977). For these reasons, a linear equation was adapted to the molting probabilities in a simple way.

The molting probability of new-shell crabs (AMN) was computed as:

$$AMN_k = \frac{m_k - ARO_k}{1 - ARO_k} \tag{11}$$

where ARO_k is the average proportion of old shell crabs in length class k.

The recruitment was described as two parameters, as proposed by Sullivan et al. (1990):

$$R_{k,t} = r_k R_t \tag{12}$$

where $R_{k,t}$ is the number of recruits entering a size class k in year t; R_t is the number of recruits entering the population in year t; and rk is the proportion of recruits entering size class k, and this parameter was described by a gamma distribution. Then the model estimated parameters α_r and β_r of this gamma distribution.

In the model, the new-shell crabs were distinguished from the old-shell crabs. The new-shell crabs have a soft exoskeleton due to their molting. On the other hand the old-shell crabs have a hard exoskeleton because they did not molt in the molting season of the current year. The number of new-shell crabs in length class k in year n+1 is shown as:

$$N_{k,n+1} = \sum_{i=1}^{k} P_{ik} A_{i,n} m_i + r_k R_{n+1} \tag{13}$$

Then the number of old-shell crabs in length class k in year n+1 is described as:

$$O_{k,n+1} = A_{k,n}(1 - m_k) \tag{14}$$

where $A_{k,n}$ is the temporary number of crabs computed as:

$$A_{k,n} = (N_{k,n} + O_{k,n})e^{-M} - C_{k,n}e^{(y-1)M} \tag{15}$$

where y is the parameter of the time lag between the survey and the fishery. In this case y equals 0.25. M is the natural mortality coefficient, which has already been estimated and used to assess the population by KFES (Mori et al. 1992). M is assumed constant over length and equals 0.35. $C_{k,n}$ is the number of crabs landed in length class k in year n. The term $A_{k,1}$ is defined as:

$$A_{k,1} = (U_{k,1} / q)e^{-M} - C_{k,1}e^{(y-1)M} \tag{16}$$

where q is fishing efficiency, a parameter of the model; and $U_{k,1}$ is the CPUE in size class k in the first year.

Parameter Estimation

Steps for parameter estimation are illustrated in Fig. 6. The parameters were estimated using nonlinear least squares approach that minimized the residual sum of squares (RSS):

$$RSS = \sum \left[(N_{k,n} + O_{k,n}) - \left(\frac{U_{k,n}}{q} \right) \right]^2 \tag{17}$$

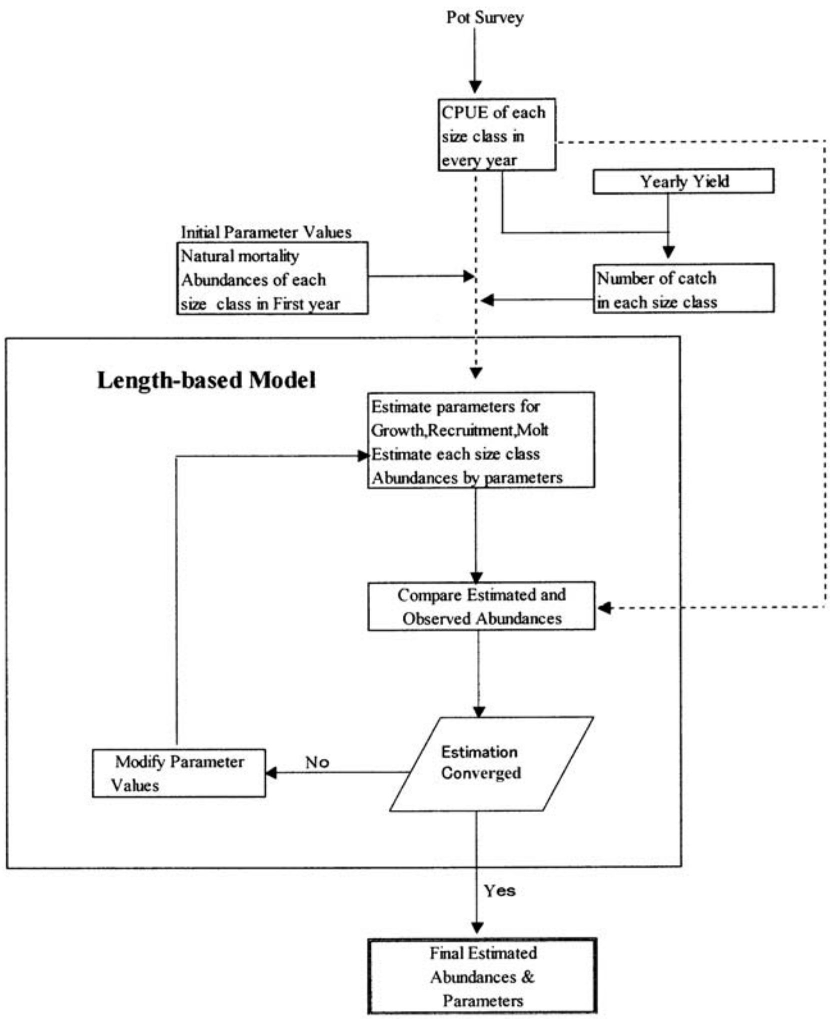

Figure 6. Flow chart of steps taken to estimate parameters and population abundance by the length-based model.

where $U_{k,n}$ is the CPUE in length class k in year n. In this objective function the old-shell crabs and the new-shell crabs are combined because our survey was executed in September, when it is difficult to distinguish between the old-shell crabs and the new-shell crabs. The parameters were estimated by using Solver in MS-Excel (Microsoft Corp.) to minimize equation 17. In Solver the restrictive conditions were set so that $q > 0$ and $a \geq 8b$. The latter restriction prevents a scenario whereby the molting probability in the largest size class is less than zero. The numbers of crabs in the first year were calculated from equation 16. In and after the second year the numbers of shell conditions in each length class were calculated from equations 13-15 with parameters, the number of crabs in the previous year, the recruitment, and the number of crabs landed. The final estimated parameters were those producing the minimum RSS in equation 17.

Results

The LPA model described well the population dynamics of eastern Hokkaido hair crab. The parameters estimated by the LPA model are shown in Table 1. In this table the standard errors of the estimated parameters are shown too. The standard errors were computed using likelihood ratios. The estimated numbers of crabs were compared with the observed numbers in Fig. 7. The observed numbers of crabs were calculated as the CPUE in the survey divided by the estimated parameter q. The estimated numbers of crabs fitted well the observed numbers.

The estimated population numbers and numbers of recruits are described in Fig. 8. The population abundance rapidly increased from 1993 to 1994 and peaked in 1995. Abundance dropped in 1996 and gradually decreased until 1998. It increased marginally in 1999. Most recruits occurred in the length 80 to 95mm (Fig. 8).

The expected molting probabilities (MP) in each length class are shown in Table 2. MP in the smallest length class was 0.45. This means that about half of the individuals belonging to this class molted in a molting season. In the three largest length classes (105 mm or larger), MPs were 0.1 or less. Molts occurred less frequently as the crabs grew. The average proportion of the old-shell crabs (ARO) in the four smallest size classes was about 0.2. Furthermore, MPs were higher than AROs in the four smallest size classes that were smaller than 100 mm in carapace length. The average proportions of molting crabs in new-shell crabs (AMN) became higher in the smaller size classes.

Discussion

One of the reasons why the management of the fishery failed was an inadequate understanding of the state of the stock, including the age structure. It is very difficult to estimate the population parameters required for stock assessment such as mortality, growth, and recruitment because hair

Table 1. Parameters estimated for hair crab of eastern Hokkaido based on a length-based population model.

Parameter	Estimated	S.E.
q	1.88×10^{-6}	0.000
β	0.493	0.348
α	0.516	0.030
b	0.065	0.009
α_r	87.632	0.138
β_r	0.390	0.020
R_{93}	1.023	0.077
R_{94}	2.417	0.077
R_{95}	2.099	0.077
R_{96}	0.602	0.078
R_{97}	0.754	0.080
R_{98}	0.189	0.083
R_{99}	0.549	0.095
RSS	1.41×10^{11}	

Unit of recruitments R_n is one million individuals.
S.E.s are standard errors of estimated parameters.

crabs cannot be aged. In such cases when age data are unavailable, the length-based models provide the best alternative. In our study a length-based model (LPA) was adapted to the population dynamics of eastern Hokkaido hair crab. Application of the model provided estimated abundances that fit the observed abundances well. From this viewpoint one may say that the LPA model can describe well the population dynamics of hair crab in eastern Hokkaido.

In addition, we note that the hair crab population in eastern Hokkaido is strongly influenced by the yearly recruitment, based on the relationship between the estimated abundances and the recruitment. High abundance is the result of strong recruitment.

From another perspective, the strong dependence on recruitment is one of the causes for the unstable stock condition. This indicates the importance of avoiding heavy fishing pressure on the recruitment to maintain long-term stability in fishery performance and yield. Therefore, there is a need to control catches of crabs smaller than 95 mm, since they make up the recruitment.

The average proportions of the old-shell crabs (ARO) in the larger size classes were higher than in the smaller size classes (Table 2). In those larger size classes, the expected molting probabilities (MP) were low. The

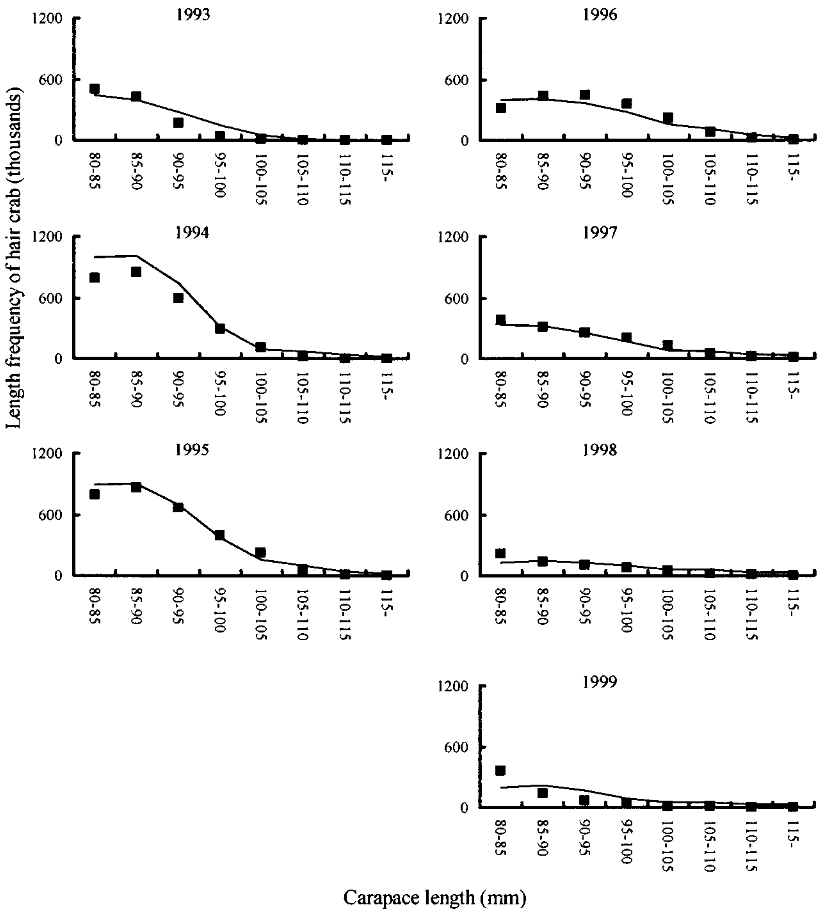

Figure 7. Comparison of observed and estimated abundance-at-length by year, 1993-1999. Black squares indicate observed values and lines indicate estimated values.

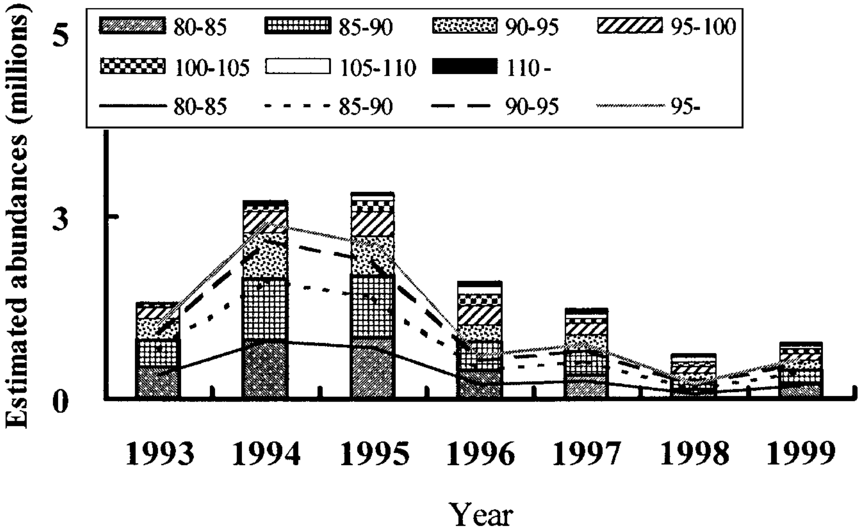

Figure 8. Estimated abundance of each length class by year, 1993-1999. The lines show recruitment by year.

Table 2. The expected molting probabilities in each length class.

	Length class (mm)							
	80-85	85-90	90-95	95-100	100-105	105-110	110-115	115-120
MP[a]	0.45	0.39	0.32	0.26	0.19	0.13	0.06	0.00
ARO[b]	0.20	0.20	0.23	0.24	0.20	0.37	0.46	0.50
AMN[c]	0.32	0.24	0.12	0.03	SA[d]	SA	SA	SA

[a]MP is the molting probability in each length class.
[b]ARO is the average proportion of the old-shell crabs.
[c]AMN is the average proportion of molted crabs in the new-shell crabs, under the assumption that all the old-shell crabs molt.
[d]SA means MPs are smaller than average.

rare occurrence of molting is the cause of those high AROs in the larger size classes.

The expected molting probability (MP) in each length class gave the other result about the frequency of molt as previously stated. Previously, it was concluded by size-related changes in distribution and tagging data (Yamamoto 1966, Abe 1992) that crabs larger than 79 mm molt every other year. However, MPs were higher than AROs in the four smallest size classes. This indicates that in these classes if all of the old-shell crabs molt, some of the new-shell crabs molt too. Note that the small size classes are abundant in this stock. In this sense, the AMNs in the smaller size classes are not low. The higher expected MPs for small-size crabs may also be caused by our assumption of a linear relationship between MP and crab size. If our linear assumption is right, ignoring the molting probabilities of the new-shell crabs will make large errors in the assessment of this stock. There is room for reconsidering the MP assumption. Further research is needed to determine the frequency of molt.

Natural mortality was assumed to be constant in this model, but in reality it is difficult to consider that natural mortality is constant for all lengths or all ages. For example, small individuals may be more subject to predation than large ones. Also, large individuals are more subject to senescence than small ones. Further research is required to refine estimates of natural mortality.

Biological reference points would be quite useful for stock management. Although our model is based on length, no reference point that is related to length has yet been developed. This model estimates the yearly recruitment. It seems possible that a yield per recruit and a spawning biomass per recruit could be calculated. However, the model relies on male crabs only. The relationship between the number of male crabs and spawning biomass needs to be resolved by further research.

The model produces only point estimates. The important role of stock assessment is to help managers make choices about dynamic fishery systems in the face of uncertainty (Hilborn and Walters 1992). In this sense, confidence intervals are needed. To accomplish this, simulation methods, sensitivity tests, or bootstrap methods may be useful.

Acknowledgments

We thank the fishermen who conducted the pot survey with KFES. We thank two anonymous reviewers for their helpful comments.

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Population Structure of Blue King Crab (*Paralithodes platypus*) in the Northwestern Bering Sea

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Abstract

In the northwestern part of the Bering Sea, large aggregations of blue king crab, *Paralithodes platypus,* are known from the Gulf of Olyutorsk to the Gulf of Anadyr. It is believed that these aggregations are portions of a single population. Maximum densities (12-21 individuals per trap) of commercial males were observed in winter at depths of 120-250 m during trapping and diving surveys in 1998-2000. Juveniles of both sexes (carapace width 21-49 mm) with densities of 7-12 individuals per m^2 were found in Glubokaya Inlet at a depth of 15 m in summer. In summer, egg-bearing females were found along the coast at depths of 6-10 m, while mature females without eggs were caught at depths of 50-80 m. In winter, egg-bearing females were caught at depths of 130-180 m, while females without eggs were not caught at all. We concluded that the Olyutorsk-Navarin population has three centers of reproduction: the Gulf of Anadyr, the area to the west of Cape Navarin, and the area of Natalia and Glubokaya inlets.

The total abundance of commercial male blue king crabs from the Gulf of Olyutorsk to Cape Navarin was approximately 3 million individuals in 2000.

Introduction

Blue king crab (*Paralithodes platypus* Brandt, 1850) is one of the most important commercial fishery resources in the Bering Sea. The species is distributed across a major part of the Bering Sea from the Gulf of Karagin in the west to the Gulf of Alaska in the east. In the Russian part of the Bering Sea, large aggregations of blue king crab are known from the Gulf of Olyutorsk to the Gulf of Anadyr. It is believed that these aggregations are portions of a single Olyutorsk-Navarin population. Several small local aggregations are also found in the Gulf of Karagin. The total annual catch of blue king crab in the Russian part of the Bering Sea during the last 10 years has fluctuated within a wide range of 800-2,500 tons and depends on climatic conditions and fishing effort.

The main stocks of blue king crab are concentrated in the area between Cape Olyutorsk and Cape Navarin. The location of aggregations has been determined by trap surveys conducted over the past 10 years. A small quantity of noncommercial males (<130 mm carapace width) was observed during those trap surveys (2-10% of all males caught). Aggregations of mature females without eggs have often been recorded. Due to these factors, a sharp decline in the number of crabs recruiting to the fished stock was anticipated in recent years. However, estimates of the number of commercial males in the stock, based on data from 1998-1999, suggested that the stock has not declined.

The main purpose of this study was to attempt to account for the relatively stable abundance level observed in recent years relative to the indicators of deterioration of recruitment. This is addressed through an improved understanding of distribution and population structure and, in particular, consideration of the location of blue king crab juveniles.

Materials and Methods

Data were sampled aboard commercial fishing vessels of 700-2,000 t of displacement using crab-trapping surveys. Catches were sampled from four trapping surveys in October 1998 to July 2000. The period from February through May was not included in any surveys. Data were also acquired from one diving survey performed in July-August 1999 (Fig. 1).

The traps used in all four surveys were parallelepipedal (i.e., having right angles and with sides lying in pairs of parallel planes). Trap sides measured 210 × 195 × 90 cm and were covered with net webbing of 7 cm mesh. Minced fish (cod, herring, or Alaska pollock) was used as bait. The traps were attached to a long string with up to 50 traps per string spaced about 100-180 m apart.

Total catch numbers were estimated for each trap in all sets. At least 100 specimens from each set were examined for biological parameters, including sex, carapace width, shell condition, and egg condition in females. Shell conditions were established as follows: shell 1 = crabs that molted not more than several days earlier (carapace is thin, soft, dirty-white in color, the legs can be practically tied in a knot); shell 2 = crabs molted not more than 2-3 weeks earlier (carapace is bright in color, unfouled, coxae of legs are white, unscratched, the chela shell is easily crushed); shell 3 = crabs molted several months earlier (carapace is bright in color, very firm, moderately fouled, coxae are yellow with brown scratches); shell 3 late = crabs molted as much as a year earlier (carapace less firm, darkened, rather dirty, heavily fouled, coxae are dark-brown with black scratches); shell 4 = premolting condition (carapace thin, dark

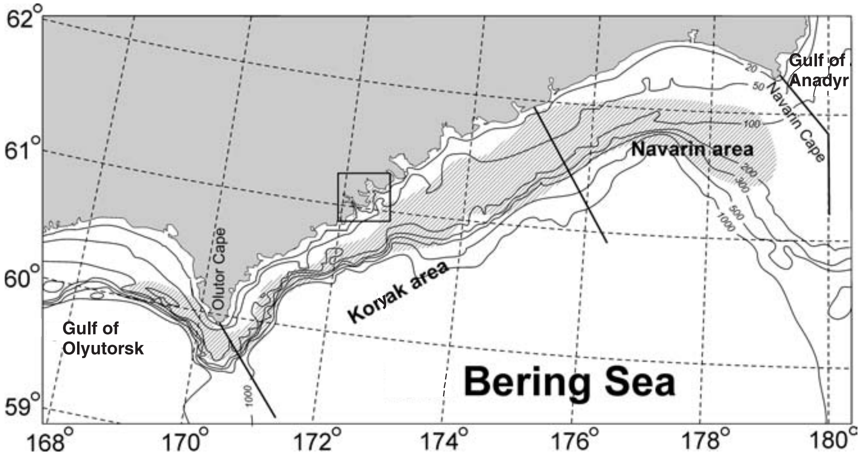

Figure 1. The study area. Trapping survey areas are indicated by the diagonal lines pattern whereas the area of diving observations is framed (Fig. 2).

in color, heavily fouled, a new thin paper-like carapace is found under the old one, coxae are black in color).

Immature females (carapace width less than 120 mm) were identified by an abdomen that is not sagged, as well as no eggs and few hairs on the short and clean abdominal legs; internal eggs at different stages of development are often found. Mature females were partitioned among four categories: (a) females bearing violet (i.e., the eggs had been extruded not more one month ago) to brown colored fertilized eggs (i.e., the eggs had been extruded within the past few months) on their abdominal legs; (b) females bearing eyed eggs (i.e., larvae will be hatched 1 to 2 weeks later); (c) females bearing empty egg cases on their abdominal legs (i.e., females that did not molt after larval hatching and did not subsequently mate); and (d) females larger than 120 mm CW bearing neither eggs nor empty egg cases on their abdominal legs (i.e., females that molted after larval hatching but did not subsequently participate in reproduction).

Two size groups were distinguished among males: those with carapace width smaller than 130 mm (noncommercial males) and those130 mm CW and larger (commercial males). A total of 32,000 crabs were examined from 2,120 sets.

To estimate crab density across a broad spatial scale, the effective fishing area (EFA) of a trap was calculated. The EFA is the area from which, on average, all crabs are removed by a single trap haul. To estimate EFA, trawling was carried out. Then, based on the trawl opening width, time, and trawling velocity we could calculate density using the formula

$$D = C / wvt,$$

where D = crab density, number of specimens per m^2; C = catch rate of crabs, number of specimens per tow; w = trawl opening width (m); v = hauling velocity (m per second); and t = hauling time (seconds).

Trawl sampling and trap sampling were carried out within a common area. We assumed that crab densities in the trawling and trapping set sites were comparable. The trap EFA was calculated by the formula

$$S = C / D,$$

where S = EFA, m^2; C = average number of crabs caught per trap.

The estimation of absolute density from trawl sampling and of EFA assumes that catchability by the survey trawl is constant and equal to 1.

Total abundance of crabs in the trap survey area was estimated. Squares (km^2) were established for each 20-30 m depth interval within the 40-330 m depth range using the VNIRO original software Mapdesigner, using the spline approximation method (Stolyarenko 1987). This depth range encompassed the commercial fishing area. Crab abundance in each square was estimated by applying the average density at these depths from the trap surveys. In performing such spatial extrapolation, we assumed that the average catch rate remains constant within each depth across the whole fishing area.

Diving surveys were carried out in the area of Natalia and Glubokaya inlets (Fig. 2). Thirty-two transects were executed at depths not exceeding 25 m.

Results

The EFA for one American trap was estimated at 45,000 m^2. Large numbers of mature females with newly extruded egg mass of violet color were found during the diving survey in July-August 1999 (Fig. 2), along the northern coast of Bogoslov Island, to the south of St. Peter Inlet, and to the east of Natalia Inlet. In these areas the density of mature females reached 1-1.5 individuals per m^2. The females were usually found below a belt of large boulders that extended from about 6 m to greater depths. Single mature females were observed at similar depths along the western coast of Bogoslov Island and near Cape Zosim. Densities of recently molted (shell 2 or 3) mature females with eggs of violet color were 0.1-0.5 individuals per m^2 at a depth of 11 m near the mouth of Glubokaya Inlet and near the Chasovye Kamni Islands (located at the entrance to Glubokaya Inlet).

Juveniles (carapace width 21-49 mm) were common off Cape Partizan in Glubokaya Inlet (Fig. 2). Juveniles of 25.9 ± 0.9 mm average carapace width formed aggregations of 7-10 individuals per m^2 at depths of 15-21 m, while at greater depths another cohort of 43.2 ± 1.6 mm juveniles formed aggregations of 10-12 individuals per m^2. The sex ratio was close to 1:1.

Commercial males were found over the whole trap survey area from Cape Navarin through the eastern part of the Gulf of Olyutorsk (Fig. 3).

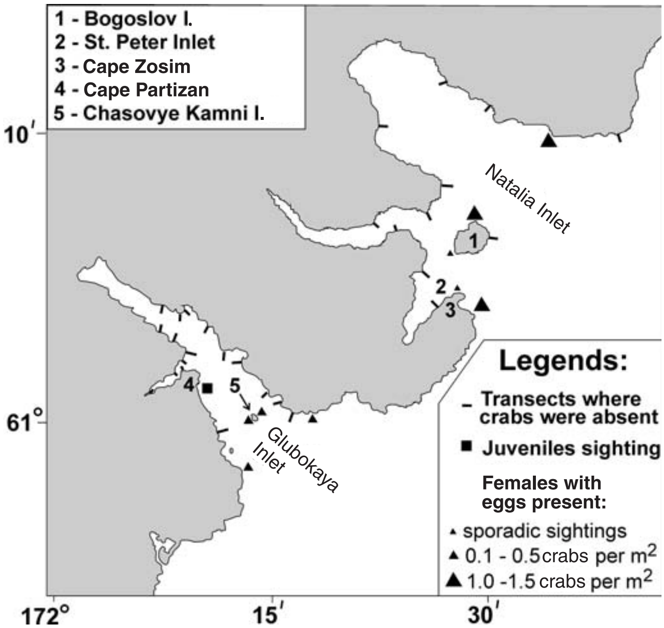

Figure 2. Diving surveys in Natalia and Glubokaya inlets in July-August 1999. The locations of all transects and those transects where females and juveniles were observed are indicated.

During the summer season commercial males do not form dense aggregations (Table 1). In this case their catch rates during two summer seasons did not exceed 6.1 individuals per trap, which is only about half the catch rates during autumn-winter (13.6 and 12.5 individuals per trap).

Generally, in summer the highest aggregations for all crab groups were recorded in the Koryak area off Natalia and Glubokaya inlets and in the Navarin area at depths of less than 60 m. During the autumn-winter season all three crab groups are found at greater depths than in summer (120-250 m). Commercial males are continuously distributed along almost the entire western coast of the Bering Sea within this depth range. The catch rate of commercial males in winter ranges from 12 to 21 crabs per trap and their total abundance from the Gulf of Olyutorsk to Cape Navarin is estimated at approximately 3 million, with 2.3, 0.6, and 0.1 million in the Navarin, Koryak, and eastern part of Olyutorsk inlet areas, respectively.

When comparing samples taken during autumn 1998–winter 1999 (when sampling was conducted in all areas of the western Bering Sea), a clear trend is evident of increased average sizes of males and females

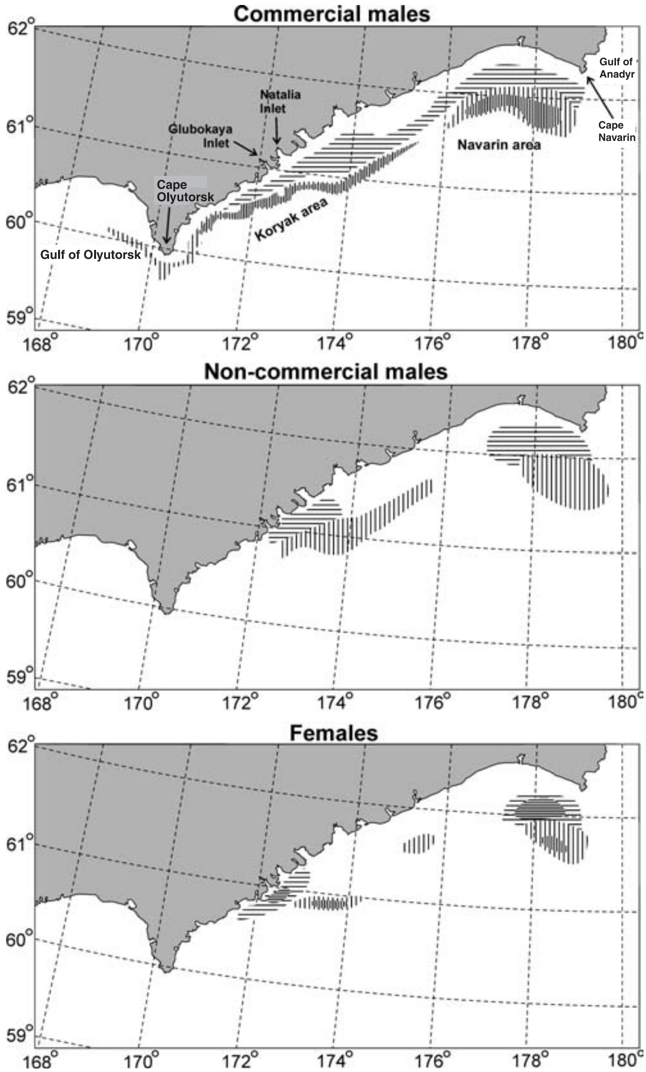

Figure 3. The distribution of commercial and noncommercial males and females. Patterned areas delineate their main distributions during the trap surveys. For commercial males and females, sparse lines mean density over 5 individuals per trap, and close lines mean density over 10 individuals per trap. For noncommercial males, patterned areas delineate distribution with density over 0.5 individuals per trap. Vertical lines denote winter season whereas horizontal lines denote summer season.

Table 1. Average season-specific catches of blue king crab by population component from trap surveys.

Period	Season	Group	Survey area (km^2)	Mean catch (number per trap)
Oct 1998-Dec 1999	Autumn-winter	Com. male	5,500	13.6
		Female	5,500	0.002
		Juv. male	5,500	0.33
Jul 1999-Sep 1999	Summer	Com. male	3,900	4.2
		Female	1,100	0.003
		Juv. male	1,100	0.3
Oct 1999-Nov 1999	Autumn	Com. male	6,500	12.5
		Female	8,400	2.9
		Juv. male	8,400	1.5
Jun 2000-Jul 2000	Summer	Com. male	15,400	6.1
		Female	4,250	3.2
		Juv. male	4,250	0.12

from east to west (Table 2). The catch rates of non-commercial males (130 mm and smaller) were maximum in the Navarin area (Table 3), about twice the maximum in the eastern part of the Koryak area, and almost zero in the western Koryak area. Catches of males of 131-170 mm carapace width were stable in all the areas, and catches of males of 171-210 mm were 6 times greater in the Koryak area than in the Navarin area. Thus, an increase in average sizes in the Olyutorsk and Navarin areas from east to west occurs mainly through an increase in the proportion of largest males.

Both noncommercial males and females displayed more aggregated distributions than did commercial males (Fig. 3). The distribution of noncommercial males and of mature females was very similar. Two sites of maximum concentrations of females and noncommercial males were apparent (Fig. 3). One was located in the eastern part of the Navarin area and the other one in the eastern part of the Koryak area off Natalia and Glubokaya inlets. In the winter of 1998 and in the summer of 1999 the sites of these aggregations were similar, differing mainly in their seasonal depth distributions. In winter these groups were concentrated at depths of 100-200 m, whereas in summer they were at depths of less than 90 m.

It was possible to distinguish two functional groups of mature females (Fig. 4): (1) In autumn (beginning with October) and in winter the great bulk of mature females caught (at depths of 80-250 m) were bearing brown egg clutches and were shell 3 (i.e., extruding of eggs had happened several months before). Females with empty egg cases and barren females were very scarce (not more than 4%). (2) In summer, in the area off Natalia

Table 2. Mean size of blue king crab males and females (and standard errors) by area during October 1998 to January 1999.

Area	Males		Females	
	Mean size (mm)	Sample size (number of crabs)	Mean size (mm)	Sample size (number of crabs)
Navarin area	158.7 ± 0.3	2,959	127.8 ± 0.5	576
Eastern Koryak area	173.9 ± 0.3	5,398	133.7 ± 0.4	1,003
Western Koryak area	179.0 ± 0.3	1,891	128.0 ± 3.0	14

Table 3. Mean catch (number per trap) of blue king crab males of three size categories by area during October 1998 to January 1999.

Area	≤130 mm	131-170 mm	171-210 mm
Navarin area	0.7	6.7	2.1
Eastern Koryak area	0.4	7.1	12.6
Western Koryak area	0.01	5.8	13.2

and Glubokaya inlets, single females with violet eggs were caught at depths of 45-110 m, while up to 80% of all mature females carried empty egg cases on their pleopods or were barren and were shell 3 late. However, as noted above, during the same period, during diving surveys in Glubokaya and Natalia inlets, practically all the mature females found in shallow waters had newly extruded eggs of violet color and were shells 2 and 3. The total number of females in the Navarin and Koryak areas was estimated at about 2.4 million and 1.0 million individuals, respectively. In the Gulf of Olyutorsk mature females were very rarely caught.

Discussion

Our survey results showed that the western Bering Sea population of blue king crab has two spawning centers: a large one in the Cape Navarin area and another one in the area of Natalia and Glubokaya inlets. In the catches taken in these centers the crabs most frequently are juveniles and two localized aggregations of females subdivided into two functional groups. It has already been established (Sasakawa 1973, 1975; Jensen et al. 1985) that blue king crab females are characterized by a biennial reproduction

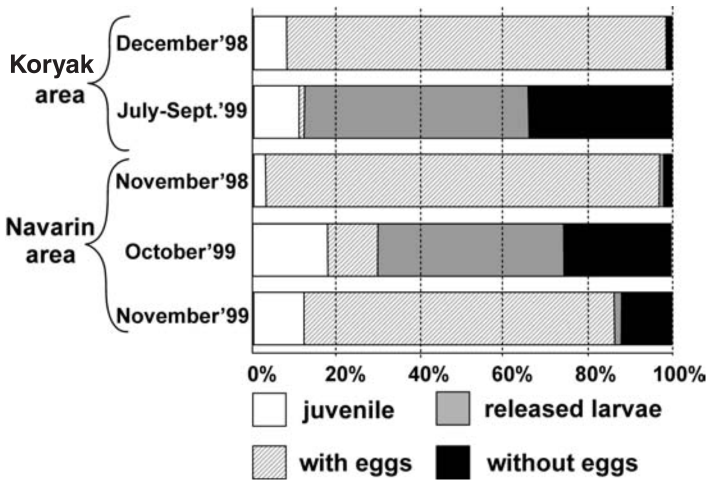

Figure 4. Percentage composition of various categories of females in different stages in the Navarin and Koryak areas.

cycle. The bulk of the first group is composed of egg-bearing females which molted and spawned in spring of the current year, and the second group consists of mature females that did not molt and spawn in spring of the current year. The remaining portion of females of both groups is composed of juvenile and very old individuals. Generally, these two functional groups of females within each aggregation are spatially separated. In summer, egg-bearing females are found near the coast at depths of 6-10 m (according to the diving survey data) and hence they were not caught in the offshore trapping survey, while mature females without eggs were caught in the trapping surveys at depths of 50-80 m. In winter, females with eggs inhabit depths of 130-180 m, while females without eggs were not caught at all. In the Navarin area over the course of October 1999, a gradual change in these groups was observed. It was supposed that seasonal migration of these groups had happened, and it was a moment when both groups were mingled. Both groups are located within a rather limited depth zone that extends about 30-50 miles along the coast.

The diving survey has shown that at least in summer juveniles form aggregations in shallow water areas. This may be why so few noncommercial males were caught by traps at depths not less than 40 m. Another reason is escapement: juveniles can simply leave the traps through the meshes.

Our surveys did not extend northeast to the Gulf of Anadyr which is also an important spawning center (Andronov et al. 2000). Thus, the Olyutorsk-Navarin population has three centers of reproduction: the Gulf of Anadyr, the area to the west of Cape Navarin, and the area within and around Natalia and Glubokaya inlets.

An increase in the proportion of large males from the east to the west may be explained by a directional migration of males throughout their lifetime.

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Methodological Problems Associated with Assessing Crab Resources Based on Trap Catch Data

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Abstract

At present, the use of trap data for estimating absolute abundance or biomass of crabs is limited by inability to quantify the relationship between trap catch rates and actual population density. The disadvantage of traps is the complex interacting effects of trap design and biological conditions on catchability of the study species by traps. Based on comparative experiments conducted to date on trawls versus various types of traps it is concluded that the current knowledge base is inadequate to allow application of trap catch rate data in absolute terms. Such data can be useful, however, in elucidating general distribution patterns and relative changes or variation in population density.

Introduction

Traditionally, studies of distribution and the population density of commercially important marine resources (in particular, crabs) in Russia have been carried out using data from trawl research catches. In recent years data from commercial fishing and research trap sampling have been increasingly utilized for that purpose. This requires a different methodological approach to data analysis and interpretation of the results obtained. The use of trap data for determination of the status of resources is limited by inability to quantify the relationship between trap catch rate and actual population density. Miller (1990) has provided a comprehensive review of the multiple variables that affect trap catch rates and their utility for estimating crab density. However, we note that research into trap-based methodologies has been rather limited. The problem of standardizing and quantifying trap catch rates is difficult because the relative impacts of multiple individual factors are unknown as is the extent and effect of their interactions. To resolve this problem it is necessary to acquire an extensive series of annual data from all relevant disciplines, including hydrography, oceanography, biochemistry, and physiology. At present, only the overall effects of complex interactions of factors have been documented and the relative effects of the individual contributing factors have remained unknown. The aim of our paper is to review the factors that affect the data acquired from trap surveys for crabs as well as to consider possible methods for applying such data in assessing crab resource status.

Materials and Methods

The catch rate data collected in the Sakhalin-Kuril region (Fig. 1), using trawls and several types of traps were used for studying the possible application of research and commercial trap surveys in assessing crab resources.

Comparison of Trawl and Trap Data

Comparative data from trap and trawl sampling were collected for each of two species of commercial crab: red king crabs (*Paralithodes camtschaticus*) and horsehair crabs (*Erimacrus isenbeckii*). The data on red king crab were collected in July 1987 near the western coast of Kamchatka (Fig. 1; Nizyaev 1991). The survey was conducted on transects that were simultaneously sampled by traps (12 stations) and trawl (6 stations). Conical Japanese-type traps were used (bottom diameter = 1.55 m, height = 0.7 m, top diameter = 0.75 m, with top entrance) and the bottom trawl used has a fishing line of 27 m length and the mesh-size of 10 mm in the codend. Catch rates, for each gear type, were adjusted relative to the gear-specific maximum catch and expressed as the proportion of the maximum. Regression analysis between the relative catch rates was conducted only for those six stations sampled by both traps and trawl.

Data on horsehair crab (*Erimacrus isenbeckii*) were collected during a trap survey in the Tatar Strait (the Sea of Japan) in June 1995 (Fig. 1) followed by a trawl survey in July. Two types of traps were (1) rectangular traps (length = 1.0 m, width = 0.75 m, and height = 0.3 m, two side entrances) and (2) domed traps with an oval bottom (maximum dimensions: length = 0.9 m, width = 0.62 m and height = 0.4 m, two side entrances). Longlines included both types of traps (25 traps of each type) arranged in a consistent configuration. Soak time varied from 2 to 3 days. Trawl sampling utilized a bottom trawl with a bottom fishing line of 35 m. Each trawl set was of 30 min duration, at a speed of 3 knots.

All the crabs from both trap and trawl catches were examined to determine sex. The mean catch per trap (in individuals) was determined for each trap longline set without considering the trap type. Carapace width

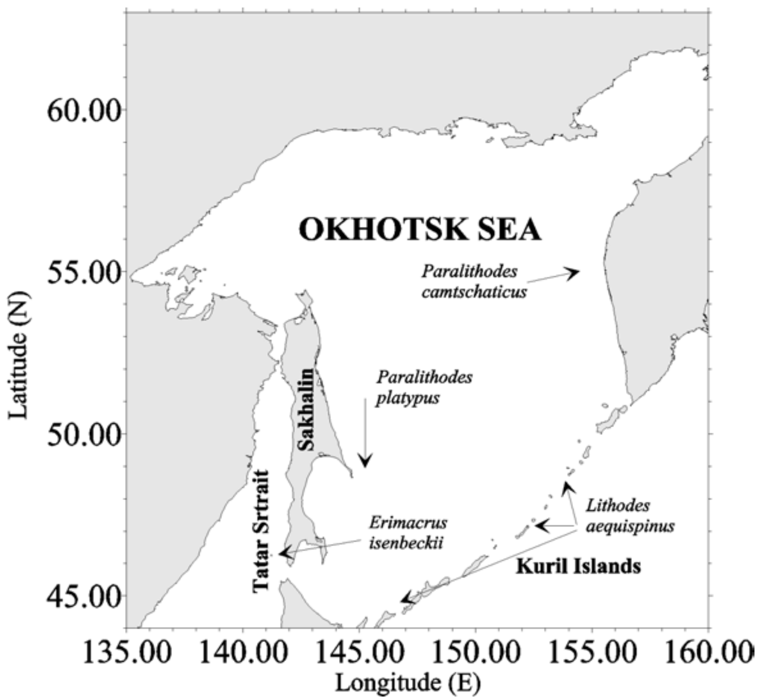

Figure 1. Location map showing regions referenced in the text.

(CW) of crabs from the trawl and trap catches was measured by caliper at an accuracy of 1 mm.

The effective trap fishing area (EFA; Miller 1975) was estimated for Japanese conical traps when used to fish hair crabs in the Tatar Strait (Sea of Japan). EFA was calculated by the formula:

$$N_i = \frac{S_i C_t}{s_t Q_t}, \qquad (1)$$

where N_i = the absolute crab abundance in area *i*; S_i = size of area *i* (km^2), where *i* represents an area of uniform catch rate) C_t = mean catch per tow from trawling; s_t= area swept by a standard trawl tow (km^2); Q= catchability of crabs by the trawl, i.e., the proportion of crabs in the swept area that are caught and retained in the trawl.

The area swept by a standard trawl set (km^2) was estimated by:

$$s_t = vat, \qquad (2)$$

where v = vessel speed (km per h), a = trawl horizontal opening (km), t = tow duration (hours).

Since absolute crab abundance and the area of distribution are independent of methodology (e.g., sampling gear) it is possible to calculate the effective fishing area of a trap using the corresponding values as follows:

$$N_i = \frac{S_i C_t}{s_t Q_t} = \frac{S_i C_p}{s_p Q_p}, \tag{3}$$

where N_i = the absolute crab abundance in area i; S_i = size of area i (km^2); C_t = mean catch per trawl set (number per tow); C_p = mean catch per trap (in number); s_t = area swept by a standard trawl set (km^2); s_p = effective fishing area of a trap (km^2); Q_t = trawl catchability; Q_p = trap catchability.

Hence it follows that:

$$EFA = s_p Q_p = \frac{C_p s_t Q_t}{C_t}, \tag{4}$$

Trawl catchability (Q_t) was taken as equal to 0.6 according to unpublished data of A.K. Klitin (SakNIRO, Yuzhno-Sakhalinsk). This value was calculated by comparing hair crab density estimates from observations using the submarine apparatus “TINRO-2” with estimates from trawl catch rates. Submarine observations preceded trawling at each station, in the Tatar Strait (Fig. 1) in 1991. Trap catchability for both trap types pooled (Q_p) is equal to 1.0, consistent with the concept of trap EFA; that on average all crabs within that area would be caught.

So, since Q_p = 1 then equation 4 simplifies to:

$$EFA = s_p = \frac{C_p s_t Q_t}{C_t}, \tag{5}$$

The second method for estimating trap EFA is one that accounts for spatial distribution patterns. It is similar to the first method in that it utilizes trawl-based area-swept catch rates and densities to estimate total abundance. The main difference is that the first method applies a single overall density estimate to the total distribution area, whereas this second method applies density estimates to multiple smaller spatial units and sums the multiple resultant abundance estimates to produce a total abundance estimate.

Absolute abundance was estimated by means of Surfer software (Golden Software, Inc.) using a kriging method (Conan 1985, Keckler 1994). Grid was calculated with 60×60, $r = 0.2$, data to use from each sector are 6. In order to convert the area of distribution and abundance obtained by the Surfer program from conventional units (calculated by the Surfer program, area = degree of latitude multiplied by degree of longitude, abundance = volume between upper and low surfers) to metric units, the following formulae were used:

$$S_i = A\alpha \text{ and } N_i = \frac{V\alpha}{sQ}\ ;\ \alpha = \cos(\varphi)\times(60\times1.853)^2 \qquad (6)$$

where S_i = total area of distribution (km^2) N or N_i = total abundance (in number of individuals), A and V = area and abundance calculated by the Surfer program in conventional units, s = fishing area (km^2), Q = coefficient catchability, cos(φ) = coefficient for conversion of a latitude degree to a longitude degree, equal to the cosine of the average latitude of the studied area, 60 × 1.853 = the number of miles per degree of latitude multiplied by the number of kilometers per mile.

The trap effective fishing area, based on the abundance estimated by the trawling data, was determined as follows:

$$\frac{V_t\alpha}{s_tQ_t} = \frac{V_p\alpha}{s_pQ_p}; \qquad (7)$$

So, since $N_t = N_p$ then

$$s_p = \frac{s_tQ_tV_p}{V_t}, \qquad (8)$$

where s_p = trap effective fishing area (EFA), V_p = abundance calculated by kriging for trawl, Q_p = trap catchability (conventional = 1), s_t = area swept by a standard trawl tow (km^2), V_t = abundance calculated by kriging the trawl data, Q_t = trawl catchability .

Comparing Catches of Two Trap Types (*Lithodes aequispinus*)

Data were collected using two trap types during commercial fishing of golden king crab (*Lithodes aequispinus*) near the North Kuril Islands (Fig. 1). Longlines of pyramidal traps (bottom dimensions = 1.75 × 1.75 m, height = 0.8 m, 2 side entrances) and of rectangular traps (bottom dimensions 2.1 × 2.1 m, height = 0.86, 2 side entrances) were consecutively set, in alternating order, on common stations, with soak times of 2-3 days. Twenty-three stations, located in areas of high crab density, were comparatively sampled using the two types of traps. Catches were partitioned among various population components: commercial males (CW > 130 mm), non-commercial males (CW ≤ 130 mm), mature females (CW > 100 mm), immature females (CW ≤ 100 mm).

Effect of Soak Time on Trap Catches

Investigation of the effect of soak time on catch rate of commercial male golden king crab (*Lithodes aequispinus*) utilized a 6-year data series (1994-1999) obtained during commercial fishing near the North and South Kuril Islands. Data were pooled over 6 years, so seasonal and annual distinctions were not determined. Three areas, with consistently high catches, were selected to minimize any impact of density variation (Fig. 1). The first area is located on the oceanic side of the Lovushka Rocks, the second one is located in the Rikord Strait, and the third one is off the southern Iturup Island toward the Sea of Okhotsk. Only pyramidal crab traps, as described earlier, were used. The end traps were not taken into account to estimate the mean catch. To standardize for annual changes in abundance, each catch was expressed as a proportion of the maximum catch for that season of year:

$$P_i = \frac{C_i}{C_{max}}; \tag{9}$$

where P_i = the proportion of the maximum catch represented by the catch at station *i*; C_i = catch rate (mean catch number per trap) at station *i*; *Cmax* = maximum catch number per trap in the studied area for corresponding season of year.

Mean catch rates (number per trap) were calculated by daily soak intervals. Soak times represented by fewer than 25 sets of traps were excluded from the analysis.

Comparing Trap Catches with Environmental Variation (Lithodes aequispinus, Paralithodes platypus)

Trap sets with the soak times of 2-4 days for which atmospheric pressure data were also available were selected for investigation of the possible effect of atmospheric pressure on golden king crab (*Lithodes aequispinus*) catch rates. Atmospheric pressure was determined daily. Changes in the atmospheric pressure were determined as the difference between the atmospheric pressure on the day of the trap hauling from the day of their setting.

Average daily catch per unit effort (CPUE, number per trap) was estimated from commercial fishery data of blue king crab (*Paralithodes platypus*) near the eastern Sakhalin coast (Fig. 1) in September-October 1993 when cyclones passed through that area. The fishing was conducted using pyramidal crab traps. About 4-6 longlines with 25-30 traps in each set were hauled in a day. Trend lines were calculated by least squares regression.

Results

Comparing Trawl and Trap Data

The short-term study on comparison of trawl and trap catch rates of red king crab near the western Kamchatka coast was conducted in July 1987 (Fig. 2).

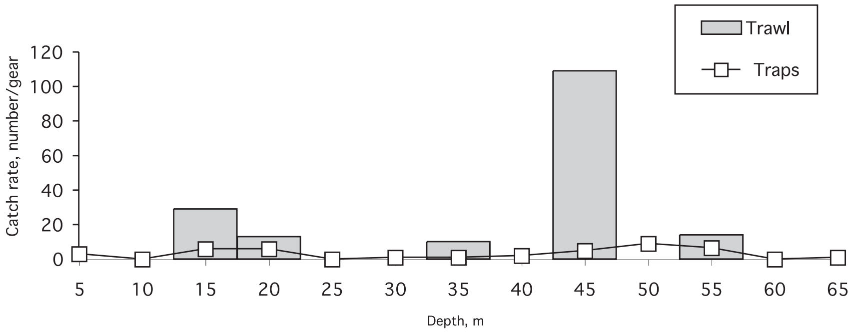

Figure 2. Bathymetric distribution of catch rates of commercial male red king crabs near the western Kamchatka coast in July 1987.

The regression analysis on the data adjusted in relation to the maximum catch showed no relationship ($R = 0.18$, $N = 6$).

Trawl and trap catch rates were also compared from surveys for horsehair crab in the southern Tatar Strait (Nizyaev and Bukin 2001). For this comparison trawl and trap surveys were carried out almost simultaneously. The distribution pattern of commercial males differed between trawl and trap data (Fig. 3). Considerable differences were apparent in the size composition of horsehair crabs from trawl and trap catches (Fig. 4). For both sexes, crabs were larger from trawl catches than from trap catches. The effective fishing area (EFA) and effective fishing radius (EFR) of Japanese traps were estimated with first way at 1,406 m^2 and 47 m respectively, second way = 2,334 m^2 and 78 m, when used to fish horsehair crab in the Tatar Strait (Table 1).

Comparing Trap Types

Only in one case of the 23 comparisons between paired sets was the catch rate of commercial-sized golden king crabs higher from the pyramidal traps than from the rectangular traps (Table 2). In most cases, the catch rates from the rectangular traps of greater capacity were several times higher than those from pyramidal traps of lesser capacity. This difference in catch rate between trap types increases with decreasing crab size (Table 2). This difference in relative catchability between trap types also increases with catch rate, being largest for above-average catch rates and smallest for below-average values. In addition, the difference in the catch rates between trap types was greater for smaller crabs than for larger crabs of both sexes.

Effect of Soak Time

Catch rates of golden king crab across several years were summarized by daily soak intervals for each of three basic fishing areas of the Kuril

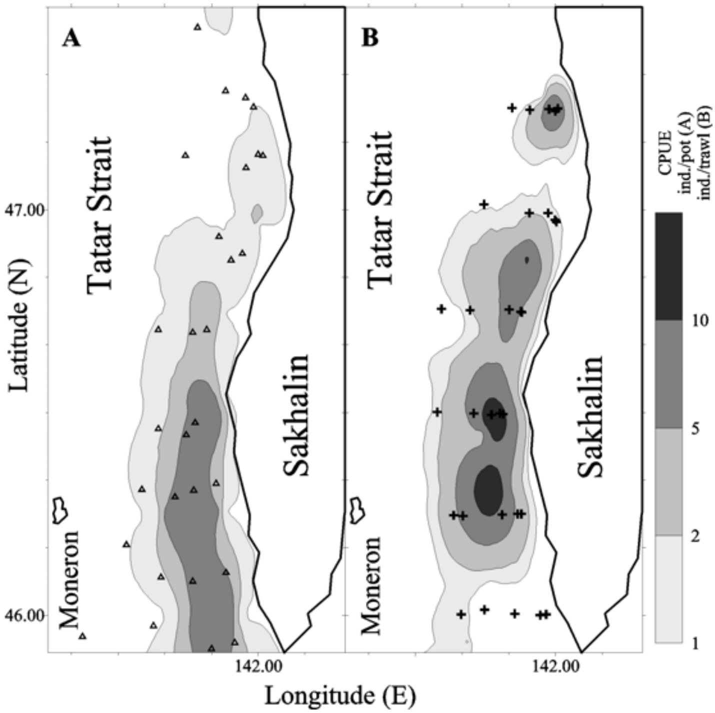

Figure 3. Station locations and distribution of commercial males of Erimacrus isenbeckii near the southwestern Sakhalin Island coast from surveys using traps (A) and trawl (B) (summer 1995).

Table 1. Calculation of trap effective fishing area for commercial-sized horsehair crab males in the southern Tatar Strait.

Sampling gear	Area (km^2)	Total abundance from trawl	Mean catch rate, number per set	Area swept and effective fishing area (m^2)	Catch-ability	Trap effective fishing radius (m)
Trawl	3,334.5	1,538,014	4.61	10,000	0.6	
Trap[a]	3,334.5	1,538,014	1.08	1,406	1.0	46.9
Trap[b]	3,334.5	1,538,014	1.08	2,334	1.0	77.8

[a]Trap effective fishing radius based on overall catch rate mean.
[b]Trap effective fishing radius based on spatial distribution and kriging.

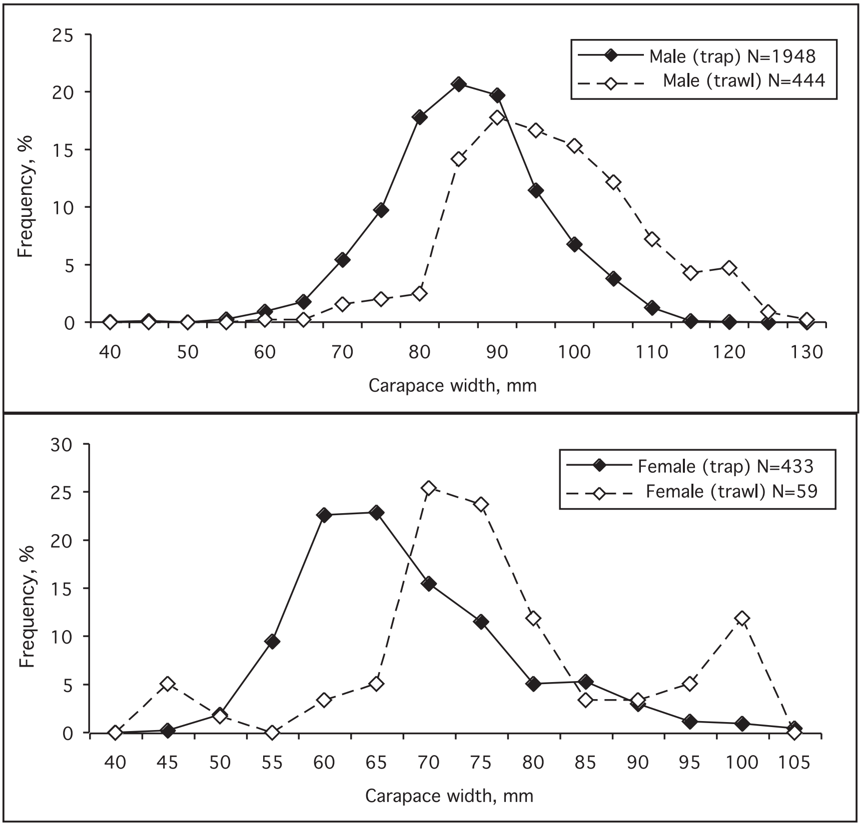

Figure 4. Size composition of Erimacrus isenbeckii individuals from trawl (July) and trap (June) catches, in1995, Tatar Strait.

Table 2. Ratio of catch rates from large rectangular traps to those from smaller pyramidal traps for four population components of golden king crab near the North Kuril Islands during 1994-1999.

	Commercial males (>130 mm CW)	Non-commercial males (<130 mm CW)	Mature females (>100 mm CW)	Immature females (<100 mm CW)
All data	2.01	3.55	2.53	2.69
For below-average catch rates	1.46	2.10	1.78	1.36
For above-average catch rates	2.43	5.63	2.91	3.38

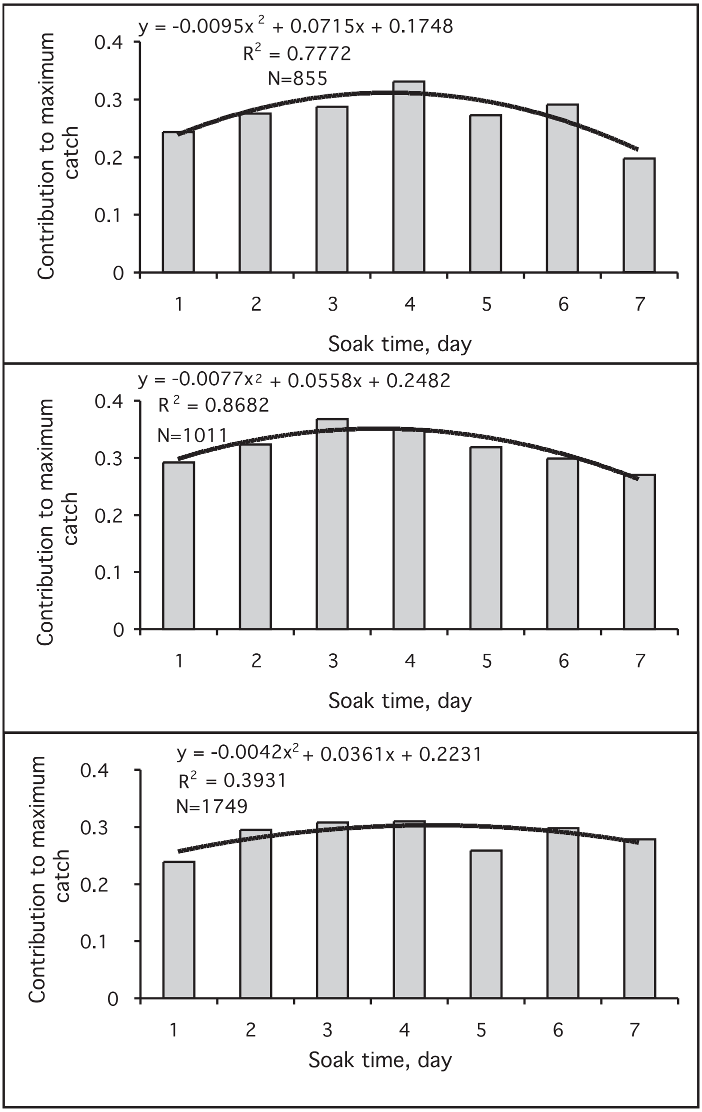

Figure 5. Relative commercial trap catch rates of golden king crab males (left) and deviations from the mean (right) in relation to soak time (trend line is a second order polynomial).

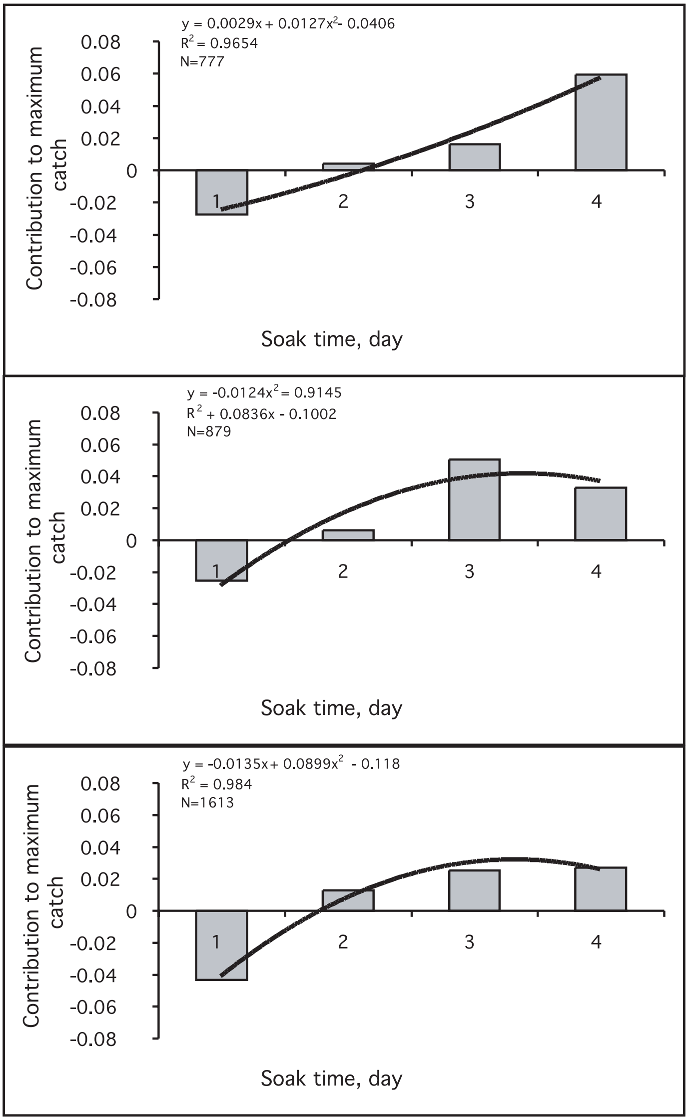

Figure 5. (Continued.)

Islands (Fig. 5). Maximum catch rates were associated with soak times of 2-4 days with catch rates decreasing over longer, and at shorter, soak times. The error associated with variation in soak time for golden king crab was about 10% on average.

Relationship of Catch Rate and Environmental Variation

Catch rate data utilized for comparison with variation in atmospheric pressure were derived from commercial fishing of blue king crab (*Paralithodes platypus*) near eastern Sakhalin (Fig. 1) in 1993. Only two cyclones passed through the area during the sampling period, and it appears that low catch rates were associated with both cyclone events (Fig. 6).

The analysis of the long-term data showed no relationship between catch rates of golden king crab and atmospheric pressure (Fig. 7). However, catch rates were related to change in atmosphere pressure (Fig. 8). This relationship was described by a quadratic equation ($r^2 = 0.83$, Fig. 8). Maximum catch rates were associated with stable or relatively small change in atmospheric pressure. In contrast, sharp change in atmospheric pressure, whether increase or decrease, was associated with reduction in catch rates.

Discussion

The effective fishing radius of Japanese traps was estimated at 47 m and 78 m, when used to fish *Erimacrus isenbeckii* in the Tatar Strait (the Sea of Japan). The difference between these two estimates was based on a difference in the methods of estimating density. For the smaller estimate (47 m) density was estimated by averaging of empirical catches over the entire area, whereas the larger estimate utilized detailed information on spatial distribution of crab density. Therefore the estimated radius of 78 m is considered the more accurate.

Our estimated effective fishing radius (EFR) of 78 m for Japanese traps, is generally comparable with those estimates for *Chionoecetes opilio* in Canadian Atlantic waters of 50-70 m by Brêthes et al. (1985) and 69 m by Greendale and Bailey (1982), but it was larger than the 36 m estimated by Miller (1975).

The considerable variation in estimates of the effective fishing area, as reflected by estimates of its radius, represents a problem with respect to estimating absolute abundance or biomass. Such variability in EFA estimates is likely related, in large part, to variation in fishing practices, and resultant variation in catchability. Only if the relationship between actual density and trap catch rate is constant, or nearly so, can it be used as an index to assess relative changes in abundance.

An example of this problem is based on the surveys carried out in July 1987 on the western Kamchatka shelf during a period when a drastic reduction in trap catch rates of red king crab was observed (Nizyaev 1991). A drop in commercial catch rate is noted every year during June-July. In the late 1980s, catch rates typically declined from 15-20 crabs per trap

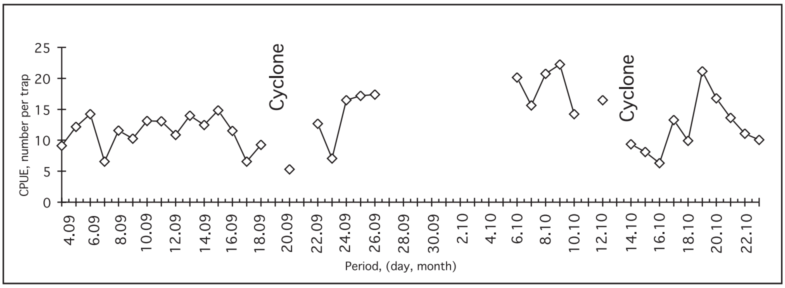

Figure 6. Daily catch rates of blue king crab in the vicinity of the eastern Sakhalin coast in relation to the passage of cyclones (1993).

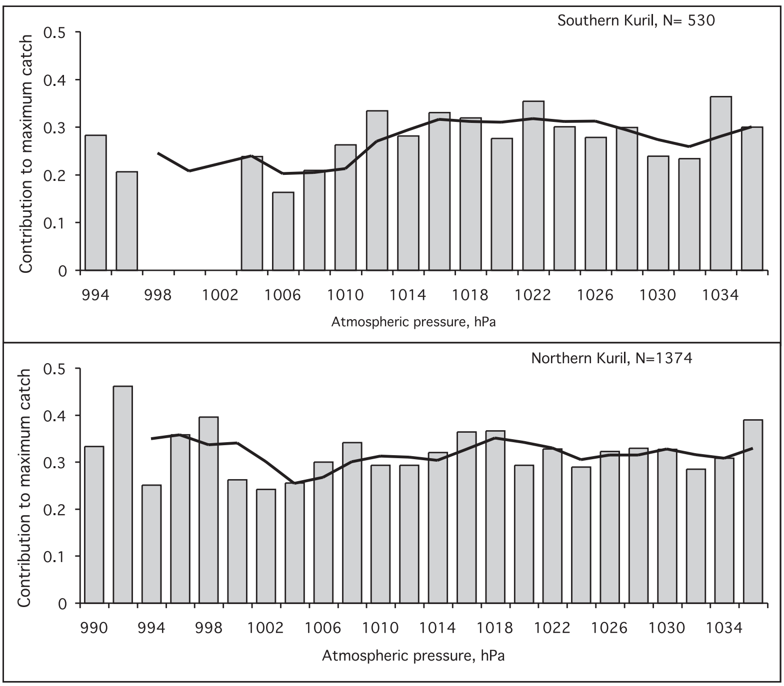

Figure 7. Relative catch rates of male golden king crabs versus atmospheric pressure (trend line is a 3-day moving average).

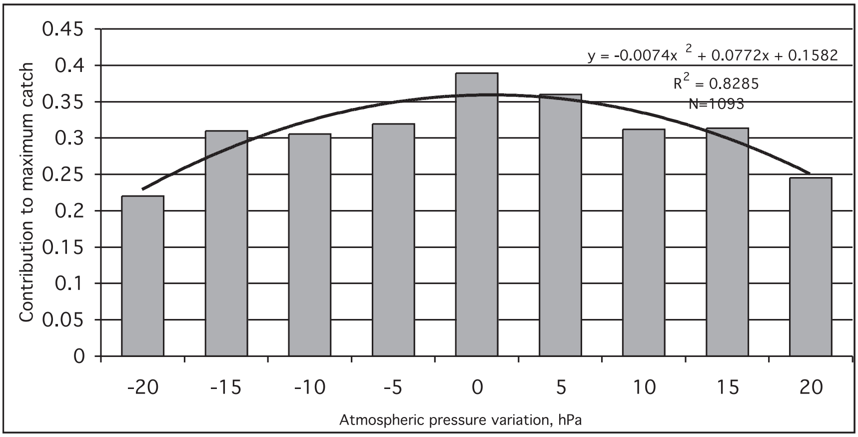

Figure 8. Relative catch rates of male golden king crabs versus atmospheric pressure variation (trend line is a second order polynomial).

haul in April-May, to about 5-10 crabs per trap haul in June-July. In 1987, catch rates (number per trap haul) decreased from 15-20 individuals in April-May to an extremely low level of 5-7 individuals in June-July, due to anomalies in molting and spawning processes. (Nizyaev et al. 1990). We conclude that, in some seasons, there may be no relationship between trap catch rate and actual crab density. We believe that this is due to considerable seasonal variation in EFA that is associated with seasonal change in biological characteristics or processes. Therefore, catch rates from any single trap survey would likely be affected by seasonally specific biological processes, which would likely be confounded with non-biological effects, such as fishing practices. For this reason, we recommend the following approaches. First, data sets should be standardized for effects of abiotic factors on catch rates. For example, our data showed that under similar conditions in three regions maximum catches are associated with soak times of 3-4 days. We also found that trap catch rates of golden king crab were negatively related to sharp changes in atmospheric pressure. By establishing such relationships it is possible to standardize for variation in soak time and atmospheric pressure. Second, surveys should be conducted using both traps and trawl with data on all relevant biotic and abiotic variables collected. Furthermore, such combined trap and trawl surveys should be conducted for the study population in all seasons, so as to determine general seasonal variation in catchability by traps and select the most suitable season for annual comparisons. We believe that this approach would control for both abiotic and biotic effects on trap catchability and so facilitate the establishment of reliable indices of abundance and biomass based on trap catch rates.

Without knowing particular relationships one can only speculate about the causal mechanisms of observed phenomena. Our data on the *Erimacrus isenbeckii* trawl and trap surveys conducted in the southern part of the Tatar Strait show that the trap catch rates generally reflect the distribution pattern determined by the results of the trawl survey. However, details are not so similar. The trap data show a more uniform density distribution than do the trawl data. The trawl survey data show relatively great spatial variability, such that areas with the highest and the lowest catch rates can be in close proximity to each other, while the density values vary gradually without drastic changes according to the trap survey data. We suppose that this difference may reflect low trap catchability in the areas with the highest density. This reflects our belief that trawl catchability is relatively constant whereas trap catchability is more variable.

The comparison of catch rates between two trap types that differed mainly in their sizes, indicated that trap catchability increased with increasing trap size or volume, but it decreased with increasing crab density. The decrease in catchability with increasing density reflects “trap saturation,” a phenomenon whereby trap catch rates do not exceed some level that is specific to each trap type, due to effects of competition. Logically, this maximum catch rate level at saturation increases with trap size or volume, as our results showed. In the areas of high density, the smaller trap type more greatly underestimated density than did the larger trap type. In our opinion, the smaller the volume of a trap the stronger would be the effect of “smoothing” across areas of high population density, which accounts for the uniform distribution of *Erimacrus isenbeckii* legal-sized males from trap data relative to that from trawl data.

Our data collected during the molting season showed that large horsehair crabs of both sexes were caught better by trawl (in July) than by trap (in June). We suppose that this is related to decrease in molting frequency with increasing age and size (Marukawa 1933, Weber 1967). Miller (1990) noted that catchability of crabs and other crustaceans by traps is related to stage in the molt cycle. Large horsehair crabs molt less frequently than smaller crabs, so the proportion of molting or newly molted crabs decreases with increasing size. We believe that traps have a higher catchability for recently molted crabs than for crabs that had not molted during the 1995 molting season.

Our experiments suggest that without an understanding of the effects of biological factors on trap catchability it is impossible to determine the true relationship between trap catch rates and population density.

Acknowledgments

We thank Earl Dawe for his constructive review, and for help with editing the manuscript.

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Alaska Sea Grant College Program • AK-SG-02-01, 2002

Inquiry for Application of Data Collected by Observers Deployed in the Eastern Bering Sea Crab Fisheries

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Abstract

At-sea observers are an integral component of commercial king crab (*Paralithodes* spp.), Tanner crab (*Chionoecetes bairdi*), and snow crab (*C. opilio*) fisheries management in the eastern Bering Sea. The Alaska Department of Fish and Game (ADFG) maintains varying levels of observer coverage on crab fishing vessels and processors to aid in achievement of short-term and long-term management objectives. These objectives include inseason assessment of fishing performance, general biological knowledge of shellfish, and bycatch for developing harvest strategies and establishing regulatory policy. This paper provides an overview of the high uses of shellfish observer data including the development of models for estimating relative stock abundance, producing preseason projections of fishery performance, and various life cycle and biological applications.

Introduction

Fishery observers have become an integral component of fisheries management for the purpose of monitoring fisheries and data collection. National standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) of 1996 states that (1) conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry; (2) conservation and management measures shall, to the extent practicable, minimize bycatch and to the extent bycatch cannot be avoided, minimize the mortality of such bycatch; and (3) collection of reliable data is essential to the effective conservation, management, and scientific understanding of the fishery resources of the United States (U.S. Department of Commerce 1996). The State of Alaska Mandatory Shellfish Observer Program has evolved to help meet the national standards. This paper discusses some of the uses of observer data from the Bering Sea king, Tanner, and snow crab fisheries.

Historic Role of Observers in Bering Sea Crab Fisheries

The Alaska Department of Fish and Game has deployed department staff as observers on vessels fishing eastern Bering Sea king crab for over two decades to collect inseason data, monitor harvests, provide data for postseason analysis, and develop management strategies and regulations. Until 1988 ADFG solicited vessels to volunteer for observer coverage. However, funding and volunteer vessels were only sporadically available. Observers were deployed during a June 1977 exploratory fishery for red king crab (*Paralithodes camtschaticus*) in the Nome section of Norton Sound to collect bycatch and catch data (ADFG 1978). Because high "dead loss" was a problem in the Nome section, seawater temperatures and salinity were also measured. In 1978 observers were deployed on the fishing grounds in both the St. Matthew and Nome sections exploratory fishery areas to collect bycatch and catch data and to tag legal-sized male red king crabs in the Nome section (ADFG 1979). Even though the red king crab catcher-processor (C/P) fleet in Bristol Bay more than tripled between 1978 and 1979 no funding was available to monitor at-sea processors for 1979 and 1980 (ADFG 1980, 1981). During the 1981-1982 Bering Sea king crab season a single observer onboard a floating processor (F/P) located in the Pribilof Islands allowed for better control of the fishery closure before the harvest guideline was greatly exceeded (ADFG 1982). The North Pacific Fisheries Management Council (NPFMC) funded observer deployments for the 1982 Bristol Bay red king crab season after the National Marine Fisheries Service (NMFS) survey revealed a marked population decline. Catch rates were very low and observer data confirmed a decrease in sexually mature females. Consequently, the season closed before the guideline harvest level (GHL) was reached (ADFG 1983). Even though personnel and funding were available, volunteer vessels were not forthcoming; consequently, onboard observers were deployed for only 2 of the 5 years between 1983 and 1987 (ADFG 1984, 1985, 1986, 1987, 1988). A more detailed history of the observer program in the Bering Sea crab fisheries since 1988 can be found in Boyle and Schwenzfeier (2001) and Morrison (1992).

Program Data Collection Objectives and Methods

Observer deployments in the eastern Bering Sea fisheries are coordinated and expedited from the ADFG office in Dutch Harbor, which is located in the eastern Aleutian Islands. Likewise, observer data are entered, edited, and managed by shellfish research personnel in the Dutch Harbor office. Once entered and edited, observer data are dispersed to Bering Sea shellfish research scientists in state and federal government agencies as well as university systems and private organizations.

The primary goals of the observer program are to determine the legality of retained crabs, collect catch composition data from sampled crab pots, and collect shell size, age, and condition information. Observers receive instruction on data gathering techniques and protocols and also evidence collection, handling, and documentation procedures. Specific data collection objectives vary between vessel types, because observers deployed on F/Ps have access only to presorted, retained catches, and those on C/P and catcher-only (F/V) vessels are able to examine the contents of fished pots prior to sorting. Comprehensive shellfish observer sample methods are outlined in the most recent edition of the ADFG Shellfish Observer Field Manual (ADFG 1998).

In general, principal sampling duties for observers onboard F/Ps include monitoring deliveries from F/Vs for regulation compliance, biological data, average weight of the catch, and to obtain confidential fishing information such as catch by statistical area, date gear type, and soak time. Observers deployed on F/Vs and C/Ps sample randomly selected pots for catch composition. Daily sampling goals (e.g., quantity of fished pots examined and number of crabs measured) for observers onboard C/Ps and F/Vs depend on a number of variables during the fishing season, including special data collection projects, numbers of observed vessels, and the order of sampling priorities established by ADFG.

Ad hoc research data collection projects are assigned to observers deployed on all vessel types, and include measuring and weighing crabs, collecting genetic and pathology samples, tagging crabs, recovering tagged crabs, sampling bycatch for handling injuries and on-deck air exposure, and documenting observations of endangered bird species. Detailed methods for these and all data collected by observers can be obtained from ADFG in Dutch Harbor.

Observer Database Utilization

Preseason Fisheries Assessment and Inseason Management

After a crab fishery GHL is established, managers analyze past fishery performance using historical data collected by observers and dockside samplers. These data are the foundation for determining management strategies during prosecution of the fishery. This was particularly critical, for example, in early January 2000 when sea ice progressed south to St. Paul Island before the planned opening of the snow crab fishery. Historical snow crab catch and effort data from observer and dockside interviews with vessel operators were consulted. Data representing fishing locations were plotted and showed that a significant percentage of the snow crab harvest grounds were covered in ice. As a result, the January 15 opening was delayed until April.

During those commercial fisheries which are managed inseason, ADFG relies on catch reports from the fishing fleet to monitor harvest. At-sea observers report numbers of crab retained and numbers of pots pulled during each reporting period. Overall fleet performance is calculated from observer reports and voluntary reports from operators of unobserved vessels.

Critical data needed for inseason management are catch per pot lift (CPUE), number of pot lifts in a reporting period, and average weight of harvested crabs. Because F/Vs are not equipped with scales that accurately weigh crabs at sea, daily average weights of 50-100 crab are reported to the department by observers onboard C/Ps. These weights are used to calculate the total weight of retained crabs for the entire fleet. During the typically short eastern Bering Sea fishing seasons, inseason observer reports are often the only timely source of average weight information available to fishery managers.

The department also relies on observers to report bycatch of female and undersized male crabs, which are helpful for identifying stock distribution, structure, and biology. In 1998 observers reported relatively high bycatch of females and undersized males during the St. Matthew blue king crab *P. platypus* fishery. Based on this bycatch information and the unusually poor fishery performance for the season, ADFG closed a high-effort and low-performance season.

Stock Assessment

Estimating relative abundance of Bering Sea, St. Matthew, and Pribilof Island king and Tanner crab stocks has historically been done using NMFS trawl survey data and area-swept analysis. Due to measurement errors in this abundance estimation method, Zheng et al. (1995a) developed a length-based analysis (LBA) for estimating population abundance which incorporates data collected by observers, dockside samplers, and the annual trawl survey. By incorporating these data, the model filters out measurement errors and improves estimates of annual population abundance used to set a harvest quota (Zheng et al. 1995b). This method was used for the first time prior to the 1995 Bristol Bay red king crab fishery, and a similar model has been constructed by Zheng et al. (1998) to estimate population abundance of Tanner crabs in Bristol Bay. Another type of abundance model, termed catch-survey analysis (CSA), has been created by Zheng et al. (1997) for the blue king crab stocks of St. Matthew Island and the Pribilof Islands which incorporates data from ADFG research surveys along with observer and commercial catch data. Imprecise estimates of female abundance from the NMFS survey, coupled with small numbers of crabs sampled by observers, have precluded development of a detailed LBA for abundance estimates of these stocks (Zheng et al. 1997). Like the LBA model, the CSA model reduces the interannual variability in abundance estimates. Pot surveys and tagging studies conducted by ADFG in 1995 and 1998 covered a much greater area around St. Matthew Island than the NMFS survey. Tag recovery and bycatch data collected by observers during subsequent commercial fisheries provide information on handling rates, movement, growth, shell aging, and reproductive condition (Blau 1996). Past observer coverage for these fisheries was limited to C/P and F/P vessels but has recently been expanded to include up to 10% coverage on F/Vs. This increased observer coverage will provide the department with a greater volume of data and thus lead to greater accuracy in both of these models.

Management Plans and Harvest Strategies

Fisheries managers and researchers developing long-term management goals for shellfish fisheries in the eastern Bering Sea utilize data collected by at-sea observers. These data are used for a number of applications including the development of models for estimating relative stock abundance, producing preseason projections of fishery performance and various life cycle and biological applications (Moore et al. 2000). In March 1990 the Alaska Board of Fisheries (BOF) adopted the fishery management plan (FMP) developed by the NPFMC for Bering Sea/Aleutian Islands king, Tanner, and snow crab stocks to provide a framework for ADFG managers when making decisions regarding a particular fishery. The FMP establishes a state and federal cooperative management regime that defers crab management to the State of Alaska with federal oversight (NPFMC 1998). The FMP has been amended and revised over the years to address changing management issues and, more recently, to promote the rebuilding of several Bering Sea crab stocks. A rebuilding plan is developed when a stock is classified by NMFS as overfished. Observer data has played a crucial role in the development and assessment of these rebuilding plans. Rebuilding plans provide a framework to improve the status of the stock and are being developed for Bering Sea Tanner and snow crab stocks and for the blue king crab stock of St. Matthew Island (amendments 11, 14, and 15, respectively, of the FMP). Each plan incorporates observer data to focus on specific issues affecting rebuilding that include bycatch control measures, handling mortality, habitat protection measures, and harvest strategies. Harvest strategies have been implemented for Bering Sea Tanner crab (5 AAC 35.508), Bristol Bay red king crab 5 AAC 34.816), and St. Matthew blue king crab (5 AAC 34.917) fisheries. Ultimately, the shellfish observer biological database provides a valuable source of information to facilitate more comprehensive management of Alaska's shellfish resources (Moore et al. 2000).

Postseason Data Analysis

Postseason, managers and researchers analyze data collected by observers to determine general or specific fishing behavior of the fleet. Several factors are studied including daily pot lifts, gear soak time, CPUE, areas fished, and average weights. This analysis is then compared to data received inseason to determine accuracy of reporting and fish ticket information.

Postseason analysis also includes a preliminary browsing, editing, and discussion of all observer data during debriefing sessions. Observers fresh from the field are able to present accurate factual and anecdotal evidence that will often confirm or dispel rumors circulating through the industry regarding weather, condition of crabs, bycatch, effectiveness of gear regulations, handling mortality, and other fishery conditions.

In-depth postseason analysis is published yearly in two ADFG reports (see Moore et al. 2000 and ADFG 2000).

Gear

The ADFG has been able to utilize observer data to address various gear-requirement issues as the shellfish observer program database has grown. Observer-collected data provide the department with a scientific foundation for reviewing proposals on gear requirements. The need for pot limits, escape mechanisms in pots, legal gear definitions, gear storage, and gear conflict issues has been addressed by ADFG using bycatch data, lost-pot statistics, gear performance, and fishing activity documented by observers.

Pot Limits

Increased fishing effort and decreased GHLs in the early 1990s shortened crab seasons and raised questions requiring immediate attention from the department and industry concerning the need to limit fishing gear on the grounds. In response to a petition submitted by industry in 1991, pot limit regulations were adopted at the 1992 BOF meeting. To meet NMFS national standards for nondiscriminatory application of pot limits, the BOF established differential pot limits in 1993 based on overall vessel length (ADFG 1999). Lost-pot and biodegradable escape mechanism data collected by observers were also analyzed to determine the level of pot limits (Tracy 1994). Following the 1996 Bristol Bay red king crab season, in which the GHL was exceeded by nearly 70%, ADFG petitioned the BOF to enact interim regulations that would provide for effective management of the fishery at low GHLs. In 1997 an 11-tiered pot-limit program based on the GHL and number of vessels registered was established (ADFG 2000). A 2-year sunset clause was attached to these regulations, within which time ADFG was to determine the effectiveness of the new pot limit regulations for inseason management and the effects of pot limits on bycatch rates of undersized males and female red king crabs (Tracy et al. 1999).

During the 1997 and 1998 Bristol Bay red king crab seasons observers were deployed on F/Vs to provide data on the effects of pot limits on fishing activity, soak time, bycatch, and the effectiveness of pot limits in meeting management objectives (Tracy et al. 1999). Observers collected data on daily effort, catch rates, bycatch rates, handling injuries, and aerial exposure times of discarded crabs prior to being returned to the sea. These data were used by the BOF when they adopted into regulation the interim pot limits for the Bristol Bay red king crab fishery (ADFG 2000).

Bycatch Control Mechanisms

The incidence of red king crab capture rates in Tanner crab pots was examined during the 1993 BOF meeting using observer data collected from 1990 through 1995 during Bering Sea Tanner crab fisheries. Additional studies performed by ADFG determined that 3-inch tunnel eye openings would allow for the entrance of legal-sized Tanner crabs into pots while restricting entrance of larger red king crabs. As a result, the maximum allowable height of tunnel eye openings for pots used in the Bering Sea Tanner and snow crab fisheries was reduced from 5 inches to 3 inches at the 1995 March BOF meeting (Tracy and Pengilly 1996).

Handling, sorting, and discarding female and undersized male king, Tanner, and snow crabs can cause mortality and injuries that have various sublethal effects such as reduced growth rates. Regulations dealing with escape mechanisms are intended to reduce bycatch rates the female and undersized male portions of king and Tanner crab stocks. Changes in gear regulations for the Bristol Bay red king crab fishery were made during the 1994 BOF meeting; the minimum size of stretch mesh webbing was increased from not less than 7.75 inches to not less than 9 inches. First implemented in 1996, regulation 5AAC 35.525 required either escape rings or escape mesh in all pots fished in Westward Region Tanner and snow crab fisheries. Minimum dimensions and quantities of escapement mesh and rings were specified although placement only stipulated installation “on the vertical plane” (Byersdorfer et al. 1997). The ADFG and NMFS completed a study using observer bycatch data comparing the effectiveness of escape mesh versus escape rings and of escape ring placement (Byersdorfer et al. 1997). Upon completion of the study, the BOF modified the escapement mechanism requirements for snow crab pots as part of the rebuilding plan for Bering Sea snow crabs (ADFG 2000). Special project data assigned to observers have been essential in documenting the effectiveness of escape rings on bycatch reduction, resulting in less time sorting and reduced incidence of bycatch handling mortality (Byrne and Cross 1997).

Gear Storage

In 1998 the BOF addressed the issue of gear storage before the opening of Bering Sea snow crab fisheries. Previous regulations allowed pot storage in waters around the Pribilof Islands shoreward of the 25 fathom isobath from September 1 through May 31, with the exception that pots could be stored in waters up to 35 fathoms 14 days before and after the commercial fishing season for snow crabs. This regulation was difficult to enforce due to tidal fluctuations and seafloor irregularities within the 35 fathom isobath. A proposal was submitted by industry to also allow gear storage within 5 nautical miles of the Pribilof Islands. Pot storage limited to the

5-mile line would drastically decrease storage area around St. Paul, but increase storage area around St. George Island. The range finder feature on a vessel's radar system would be used to ensure gear storage was within the 5-mile area. Fishing locations from pots sampled by observers during the 1996 through 1998 snow crab fisheries indicated minimal fishing activity occurred in waters just beyond the 35 fathom isobath around St. George Island but inside the 5-mile line. With this information ADFG determined this proposal would not affect manageability of the fishery, thus BOF adopted the proposal and amended the regulations to allow gear storage inside either the 5 nautical-mile line or the 35 fathom isobath for Bering Sea snow crab fisheries (5AAC 35.527 D).

Area Boundaries

Concerns about Tanner crab and red king crab bycatch in the Bristol Bay crab fishing grounds surfaced in 1992. Traditionally the Bristol Bay red king crab fishery opened November 1 until closed by emergency order. The Bering Sea Tanner crab fishery commenced 7 days following closure of the red king crab fishery. A portion of the Tanner crab grounds overlap the red king crab grounds in Bristol Bay. Observer bycatch data were analyzed to determine whether bycatch of red king crabs was high during directed Tanner crab fishing. There was enough bycatch to warrant concern. In 1993 the BOF adopted regulations to open and close the Bering Sea east of 168ºW to fishing for Tanner crabs concurrent to the regulatory opening and emergency order closure of the Bristol Bay red king crab fishery. This regulation combining the king and Tanner crab seasons was intended to utilize the incidental catch of legal Tanner crabs during the red king crab fishery and preserve harvest opportunity east of 163ºW (Donn Tracy, ADFG, Kodiak, pers. comm.). The BOF also reopened the Bering Sea between 163ºW and 173ºW for directed Tanner crab fisheries 10 days following closure of the Bristol Bay red king crab fishery. In 1999 these coordinates changed to between 163ºW and 166ºW to protect two discrete populations of Bering Sea Tanner crabs. The changes were implemented by the BOF as part of the Bering Sea Tanner crab harvest strategy. Observer data were used to distinguish two separate Tanner crab stocks, one near the Pribilof Islands and the other in Bristol Bay (Rance Morrison, ADFG, Dutch Harbor, pers. comm.). In addition, to utilize incidental catch and preserve harvest opportunity, Tanner crabs may also be retained during the snow crab season when there is a harvestable surplus of Tanner crabs.

Additional Observer Data Collections

Species Identification

After the opening of the snow crab fishery on January 15, 1992, ADFG received complaints from industry attempting to use eye color alone to distinguish Tanner crabs from snow crabs. Due to difficulty in determining eye color in varying light conditions, many court cases involving the retention of undersized male Tanner crabs were dismissed. Observers were asked to document retention of Tanner crabs during snow crab fisheries. These data demonstrated that using only eye color was not sufficient to distinguish undersized male Tanner crabs from hybrids of Tanner and snow crabs. An emergency regulation was issued on January 24, 1992, requiring both eye color and mouth shape to discriminate Tanner crabs from Tanner-snow crab hybrids and snow crabs (ADFG 1994).

Bird Documentation

The ADFG, NMFS, and U.S. Fish and Wildlife Service have requested that observers deployed on commercial crab fishing vessels collect information regarding bird species whose populations are at low levels or declining, particularly spectacled eiders (ADFG, NMFS, USFWS 1995). Mortality, activity, vessel and gear interactions, incidental take, leg-band recovery, and endangered species documentation provide valuable information that can be used to assess mortality by taxa and provide other information that may be used to develop methods of reducing mortality due to collisions with vessels or interactions with fishing gear.

Stock Biology and Life History

Knowledge of the life cycles and general biology of shellfish has been greatly enhanced by the work of onboard shellfish observers. In many circumstances observers are the only means of gathering biological information from unsurveyed stocks or from surveyed stocks during the commercial fisheries. Data collected by observers were used in *Biological Field Techniques for Chionoecetes Crabs* by Jadamec et al. (1999). This guide, which includes a taxonomic key, life history, anatomy, morphometrics, reproductive conditions, shell-age classification, and other biological features of *Chionoecetes* spp., enables standardization of data collected by fisheries observers and shoreside samplers, shellfish biologists, and fishermen. Accurate data collection and consistency in methodologies are essential for sound fisheries management of all five species of *Chionoecetes* that are harvested commercially (Jadamec et al. 1999).

Estimated size at recruitment has been calculated for commercially important king crab stocks. The objective of this size-at-recruitment investigation was to examine relationships between carapace length and carapace width and to estimate the true mean carapace length at minimum legal size for the subsample data (Tracy 1998a). For blue king crabs observers measured carapace width and length of male crabs that were randomly selected from pots fished by several vessels during the commercial fishery (Tracy 1998a). Size at recruitment was also studied for Tanner crab stocks to determine the relationship between carapace length and greatest carapace width in a subsample of males and to estimate the true mean carapace width at recruitment (Tracy 1998b).

During bycatch sampling or ad hoc research projects shellfish observers collect data on parasites and pathogens of crabs, including

Table 1. Bering Sea, Aleutian Islands, and Alaska Peninsula commercial shellfish issues addressed by the Alaska Board of Fisheries since 1993 where relevant information derived from at-sea observer deployments was presented to board members by department staff.

Date	Fishery	Issue	Referenced observer data
Feb 1993	Bering Sea Tanner crab	Red king crab bycatch	Bycatch data from sampled pots
Feb 1993	Bristol Bay red king crab	Red king crab bycatch	Bycatch data from sampled pots
Feb 1993	Bering Sea Tanner crab	Tunnel eye restrictions, closed area	Bycatch data from sampled pots
Feb 1993	Bering Sea Tanner, snow, and king crab; Bristol Bay red king crab	Pot limits	Bycatch data from sampled pots and lost pot statistics
Feb 1993	Bering Sea Tanner and snow crab	Species identification	Data from sampled pots (documentation of Tanner-snow hybrid crab retained in respective fisheries); retention of illegal Tanner crab in snow crab fishery
Mar 1994	Bering Sea hair crab	Definition of a hair crab pot	Bycatch data from sampled pots
Mar 1994	Bering Sea hair crab	Size limit	Data from sampled pots and catch data
Mar 1994	Bristol Bay red king crab	Revised pot escape mesh requirement	Bycatch data from sampled pots
Feb 1995	Adak red king crab	Stock status	Bycatch data from sampled pots and catch data
Mar 1996	Bering Sea Tanner crab	Continuance of area closure	Bycatch data from sampled pots
Mar 1996	Bering Sea Tanner and snow crab	Possible conflicts of proposed gear storage with Pribilofs hair crab fishery	Data from sampled pots (sample locations from hair crab fishery)

Table 1. (Continued.)

Date	Fishery	Issue	Referenced observer data
Mar 1996	South Peninsula grooved Tanner crab	Possible conflicts of proposed longlining with sable fish fishery	Data from sampled pots (sample depths from South Peninsula grooved Tanner crab fishery)
Mar 1996	Kodiak /South Peninsula grooved Tanner crab	Pot limits	Bycatch data from sampled pots and lost pot statistics
Mar 1996	Adak/Dutch Harbor king crab	Merging of Adak and Dutch Harbor into single management area	Data from sampled pots (catch size and vessel effort distribution)
Mar 1996	Aleutian Islands deep water king and Tanner crab	ADFG to specify size, type, and configuration of commercial pots; plus escape mechanisms	Data from sampled pots (bycatch and catch size distribution); documentation of escape mechanisms used voluntarily
Mar 1996	Bristol Bay red king crab	Revised stock rebuilding strategy	Data from sampled pots (bycatch and catch size distribution)
Mar 1996	Bristol Bay red king crab	Proposed size limit reduction from 6.5 to 6 inches	Data from sampled pots (spatial association of 6 inch crabs in areas of current vessel effort)
Mar 1999	Bristol Bay red king crab	Harvest strategy, 11 tier pot limit	Catch data: pilot house logs (temporal behavior of fleet)
Mar 1999	Aleutian Islands deep water king and Tanner crab	Gear storage depths	Data from sampled pots (depth and location)
Mar 1999	Bering Sea king and Tanner crab	Gear storage depths	Data from sampled pots (depth and location)
Mar 1999	Bering Sea Tanner crab	Management Plan and harvest strategy	Bycatch data from sampled pots and catch data

Briarosaccus callosus, nemertean worms, bitter crab disease, black mat syndrome, cottage cheese disease, pepper crab disease, leeches, and chitinoclastic bacteria (ADFG 1998). Shellfish observers collected blood smears and blood samples from snow crabs for NMFS research on bitter crab disease. Observers also have been instrumental in collecting specimens for genetic stock identification (Merkouris 1998).

Summary

The MSFCMA mandates collection of reliable data for fisheries conservation and management. Even though ADFG continues to collect retained catch data shore-side, ADFG relies on data collected on the fishing grounds by at-sea observers who are in a unique position to collect specific and accurate baseline data. The ADFG Westward Region shellfish observer database had accumulated enough data to become an important source of objective information for fisheries management and research. The applications discussed in this paper are a few examples of the value of observer data. Table 1 summarizes issues addressed by the BOF since 1993 where relevant information was derived from observer data. A bibliography of literature and published reports that utilize fishery observer data is forthcoming.

Acknowledgments

This is contribution PP-207 of the Alaska Department of Fish and Game, Commercial Fisheries Division, Juneau.

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