Application of a Catch-Survey Analysis to Blue King Crab Stocks Near Pribilof and St. Matthew Islands

J. Zheng, M. C. Murphy, and G. H. Kruse

Reprinted from the
Alaska Fishery Research Bulletin
Vol. 4 No. 1, Summer 1997

Alaska Fishery Research Bulletin 4(1):62–74. 1997.

Application of a Catch-Survey Analysis to Blue King Crab Stocks Near Pribilof and St. Matthew Islands

J. Zheng, M. C. Murphy, and G. H. Kruse

ABSTRACT: A catch-survey analysis was conducted on 2 blue king crab *Paralithodes platypus* stocks near Pribilof and St. Matthew Islands of the eastern Bering Sea. Total annual catch and observed relative survey abundance of legal-sized crabs were classified into recruits and postrecruits by shell age and size and analyzed with a maximum likelihood approach. This analysis separates measurement errors from the true changes in population abundance and converts the relative abundance to an absolute value. The analysis provides smoothed annual estimates of legal blue king crab abundance for both stocks. In both areas, legal male abundances appear to be rebuilding slowly from depressed stock levels of the mid 1980s. Based on a reasonable instantaneous natural mortality range of 0.16 to 0.35 for both crab stocks, (1) postrecruit catchability is about 1.98–2.07 for the Pribilof Islands stock and about 1.20–1.38 for the St. Matthew Island stock, and (2) the ratios of recruit-to-postrecruit catchabilities for both stocks are <1.05. Because of confounded effects among catchability, recruit-to-postrecruit catchability ratio, and natural mortality, additional information is needed to separately estimate 2 of these 3 parameters.

INTRODUCTION

In the eastern Bering Sea, blue king crabs *Paralithodes platypus* are found in waters surrounding the Pribilof Islands and St. Matthew Island. The insular distribution of the species has been substantiated by annual trawl surveys (Stevens et al. 1996). Mark-recapture studies produced no evidence of migration between the 2 areas (Otto and Cummiskey 1990). Blue king crab habitat near the islands is characterized by patches of cobble, gravel, and rock, whereas the shelf substrate between the islands is primarily mud and sand.

The maximum size of adult blue king crabs, mean size at maturity, and molting probability are greater near the Pribilof Islands than near St. Matthew Island (Somerton and MacIntosh 1983; Otto and Cummiskey 1990; Paul et al. 1991). However, Otto and Cummiskey (1990) concluded, from analysis of tagging data, that growth increments are similar. Size differences are reflected by minimum legal size limits of 165 mm (6.5 in) carapace width for Pribilof Islands and 140 mm (5.5 in) for St. Matthew Island.

Commercial fisheries for these 2 stocks are managed separately, based on their allopatric distribution and different life history characteristics, but the same harvest strategy is followed. That is, if the abundance of mature males is above a minimum threshold for the stock, a 20% exploitation rate is applied to the estimated abundance that year (Pengilly and Schmidt 1995). Commercial fisheries are prosecuted during concurrent fall seasons, which close on the date the target harvest level is projected to be taken.

The blue king crab fishery in the Pribilof Islands was developed by the Japanese beginning in 1965; their harvests peaked in 1969 at 2,486 t, which composed 45% of their king crab harvest in the Bering Sea that year. During the early 1970s, blue king crabs were primarily harvested incidental to snow *Chionoecetes opilio* and Tanner *Chionoecetes bairdi* crab fishing (Otto 1981, 1990). The U.S. fishery began targeting blue king crabs in 1973, when 8 vessels took 579 t, and peaked in 1980 at 4,960 t. Vessel participation peaked at 126 vessels in 1983, but harvests declined that year to 20% of the 1980 level. Vessel effort and harvest plummeted in 1984 and remained low until the fishery was closed in 1988 due to low survey estimates of abundance.

Following baseline biological surveys related to oil exploration, which revealed a harvestable blue

---

Authors: J. ZHENG and M. C. MURPHY are biometricians and G. H. KRUSE is a marine fisheries scientist with the Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, P.O. Box 25526, Juneau, AK 99802-5526.

Acknowledgments: J. E. Reeves, R. S. Otto, and B. G. Stevens, National Marine Fisheries Service — provided survey data of Pribilof and St. Matthew Islands blue king crabs. J. S. Collie — reviewed the manuscript.

Project Sponsorship: This paper was funded in part by a cooperative agreement from the National Oceanic and Atmospheric Administration (NOAA) and in part by the Alaska Department of Fish and Game. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

king crab population, commercial interest in St. Matthew Island blue king crab developed (Otto 1990), and in 1977, 10 U.S. vessels harvested 545 t. Harvests peaked in 1983 when 164 vessels landed 4,288 t. The fishery was fairly stable from 1986 to 1991 with a mean harvest of 731 t taken by <70 vessels. Participation jumped from 68 vessels in 1991 to 174 vessels in 1992 and has stabilized at about 90 vessels since 1993.

Given rapid escalation of effort in the St. Matthew Island fishery, concurrent openings were established in 1993 for the Pribilof and St. Matthew Islands fisheries; this divided vessel effort between both fisheries. In addition, pot limits were established in 1993 to reduce total fishing effort and improve manageability of the relatively small allowable harvests. In the Pribilof Islands District, a 40-pot limit was adopted for vessels <38.1 m (125 ft) and a 50-pot limit for vessels >38.1 m (Morrison et al. 1996). The reduction in pots registered per vessel was offset by an increase of 200% in vessels compared to the area's last fishery in 1987. This resulted in an overall decline in pots pulled of only 14%. In the St. Matthew Island fishery, limits of 60 pots were adopted for vessels <38.1 m and 75 pots for those >38.1 m, which reduced the number of pots registered in 1993 to 33% of the pots in 1992 (Morrison et al. 1996). The number of vessels that participated declined by almost 50%, probably because of the concurrent seasons and reopening of the waters surrounding the Pribilof Islands for red king crab *Paralithodes camtschaticus* fishing. However, the number of pots pulled in the fishery increased slightly because the season length doubled and pot turnover rates increased.

The National Marine Fisheries Service (NMFS) initiated annual trawl surveys of the waters surrounding the Pribilof Islands in 1974 and St. Matthew Island in 1978. Area-swept methods have been used to calculate separate trawl-survey indices of absolute abundance for these 2 stocks (Stevens et al. 1996). However, direct survey estimates of abundance are affected by survey measurement errors due to crab distribution, gear performance, and other factors. Measurement errors may be large for trawl surveys because the terrain in these 2 areas is untrawlable in places or is sometimes a cobble-gravel-rock substrate that impedes gear performance (Otto et al. 1981). Juvenile and female crabs, in particular, are poorly assessed because they tend to occupy the rugged untrawlable habitat. Imprecise estimates of female abundance, coupled with small numbers of crabs caught and measured, have precluded development of a detailed length-based analysis (e.g., Zheng et al. 1995a, 1995b) for abundance estimates of these stocks.

In an attempt to distinguish survey measurement errors from the true changes in population abundance, we constructed a catch-survey analysis (Collie and Kruse *in press*) of these 2 blue king crab stocks, treating them as separate stocks with separate abundances. This analysis smoothes out the interannual variability in estimated abundance, thereby increasing the stability of annual harvest guidelines. Because the analysis depends on catch data, we limited our applications to estimating legal males only.

METHODS

Analysis of Trawl-Survey Data

NMFS survey data prior to 1980 are incomplete, so only data from 1980 to 1996 were used in this study (reported annually by NMFS, e.g., Stevens et al. 1996). With a survey grid of about 20x20 nautical miles (nmi) square covering the Bering Sea, a survey station was assigned to each square (Figure 1). One or more hauls were towed within a single station depending on crab densities.

NMFS annually poststratifies the survey stations around the Pribilof and St. Matthew Islands according to crab density because station density varies considerably between years. This poststratification history was incompletely documented, so we could not reconstruct the stratification each year. Because strata were fairly consistent in recent years, we used a constant stratification for 1980 to 1996 similar to that used by NMFS in 1996 (R. Otto, NMFS, Kodiak Laboratory, personal communication). Our stratification groups adjacent stations with similar tows per station into a single stratum to help account for the patchiness of crab distribution.

Two or more strata were used for survey stations within the Pribilof Islands District of the Bering Sea (south of 58°39'N and west of 168°W; Figure 1). All stations in the Pribilof Islands District outside the solid-line square composed 1 stratum. Typically, crab densities in this area were low, and 1 haul was made for each station in this stratum. Most crabs occurred within the solid-line area of Figure 1, where each station was normally sampled twice. However, sometimes location errors misplaced some hauls, leaving some stations with 1 haul and others with 3 hauls. The second stratum included all stations inside the solid-line square that had 1–3 hauls. Upon occasion, high densities of crabs were found at a station, in which case 4–5 hauls were made. Each station with 4 or more hauls within the solid-line square composed a separate additional stratum.

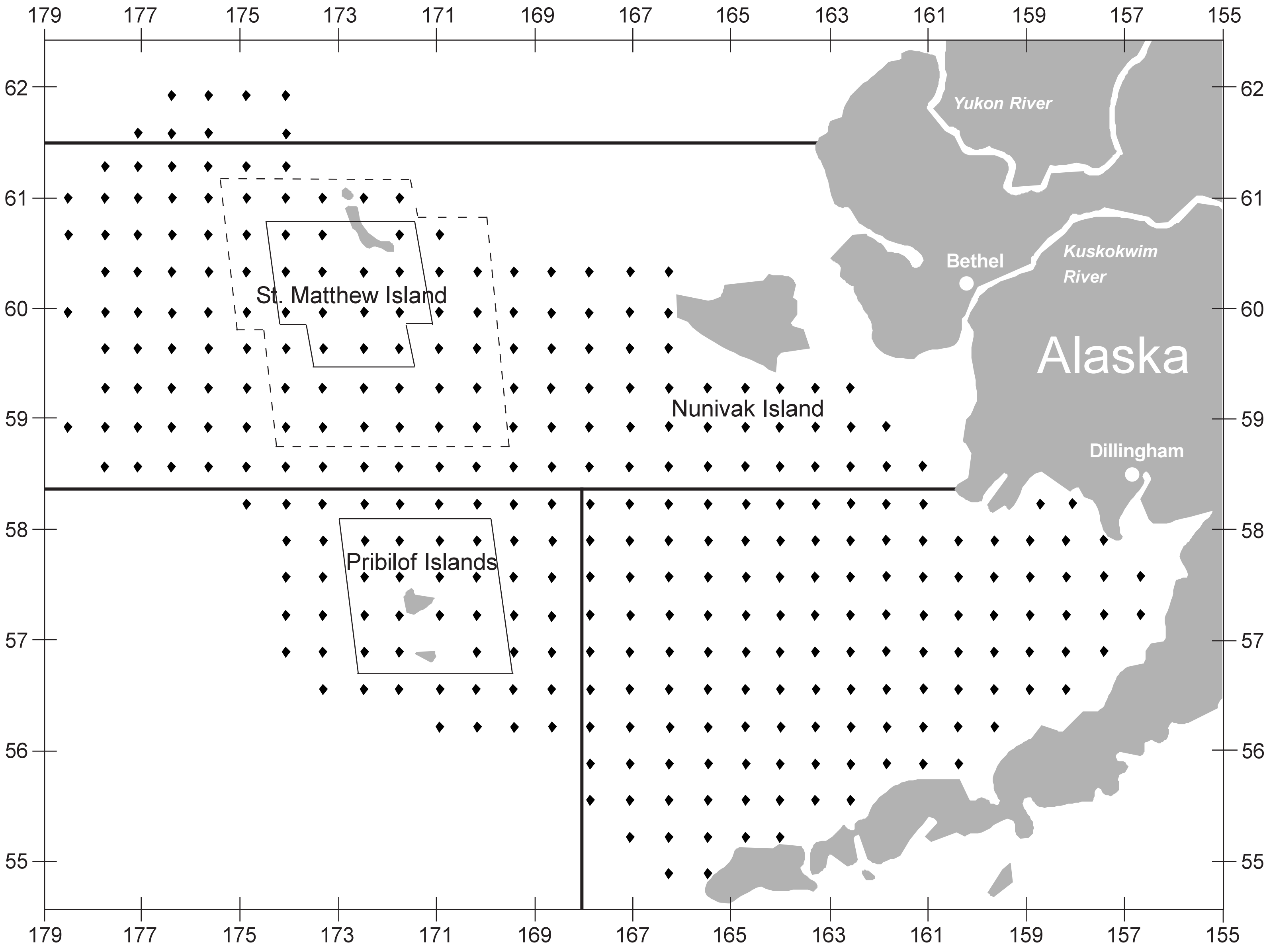

Figure 1. Survey station stratification for the St. Matthew Island and Pribilof Islands Districts in the eastern Bering Sea (modified from Stevens et al. [1996]). Each diamond represents the standard trawl location for the station, solid and dashed lines denote strata boundaries, and bold solid lines represent district boundaries.

Three or more strata were adopted for survey stations within the St. Matthew Island Section of the Northern District of the Bering Sea (north of 58°39'N and south of 61°49'N; Figure 1). Stations outside the dotted-line area (Figure 1) and within the St. Matthew Island Section belong to the first stratum; the second stratum included all stations outside the solid line but inside the dotted-line area; and the third stratum covered all stations inside the solid-line area, except those stations with >3 hauls. Two hauls were normally made for stations inside the solid-line area and 1 haul for stations outside the solid-line area. As in the Pribilof Islands District, each station with 4 or more hauls composed an additional stratum. These occasional single-station strata were usually within the solid-line area, but sometimes occurred outside the solid-line area. Crab densities were lowest in the first stratum and highest in the third stratum.

The *area-swept* approach (Alverson and Pereyra 1969) was used to estimate average crab density per 1 nmi^2 for each stratum. Crab abundances by length, sex, and shell condition were estimated for each stratum by multiplying average crab density per square nautical mile times total square nautical miles in the stratum. Total abundance of Pribilof and St. Matthew Islands blue king crabs was estimated by summing abundances from all strata for each area. Our area-swept estimates of legal crab abundance were similar to those reported by NMFS in most years (Figure 2); for convenience we refer to our area-swept estimates of abundance as the *observed relative abundance.*

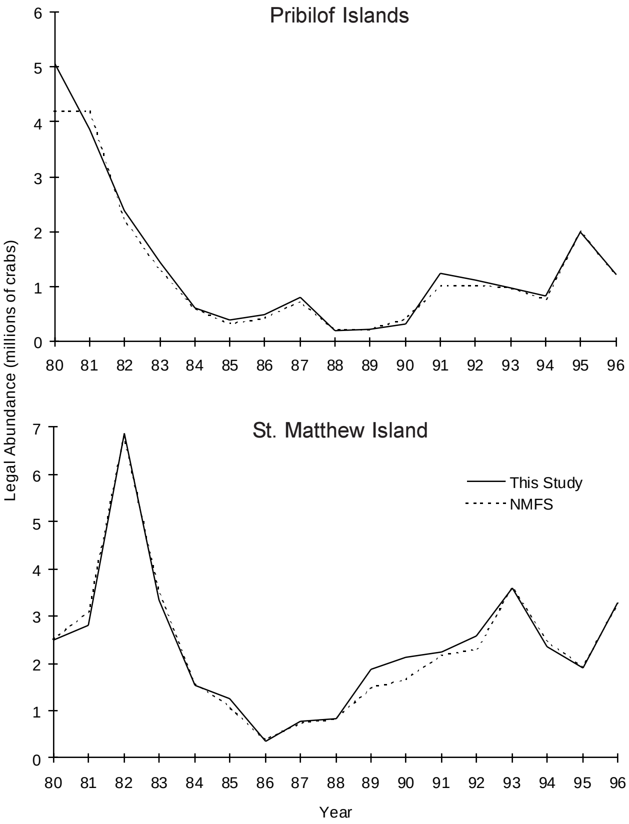

Figure 2. Comparisons of area-swept estimates of legal blue king crab relative abundance by NMFS (dotted line) and in this study (solid line) for the Pribilof Islands and St. Matthew Island Districts.

Catch-Survey Analysis

We estimated abundance of legal blue king crabs with the catch-survey analysis (CSA) developed by Kruse and Collie (1991) and Collie and Kruse (*in press*). A useful feature of CSA, aside from separating measurement errors from true changes in stock abundance, is that survey catchability coefficients can be estimated, provided natural mortality is estimable. This is of particular interest for the Pribilof and St. Matthew Islands blue king crab stocks, where it is widely held that the trawl survey does not fully cover the fishable stock due to the prevalence of untrawlable habitats, although those areas are commercially fished with crab pots.

Only legal male crab abundance is modeled by CSA. Legal male blue king crabs have a carapace length (CL) ≥135 mm for the Pribilof Islands and ≥120 mm for St. Matthew Island. The average growth increment per molt for legal male crabs is about 14 mm CL for both stocks (Otto and Cummiskey 1990). Based on the approach by Kruse and Collie (1991) and Collie and Kruse (*in press*), we categorized legal blue king crabs into recruits and postrecruits. Pribilof Islands recruits were defined as new-shell (molted within the past 12 months) males 135–148 mm CL, whereas St. Matthew Island recruits were 120–133 mm CL. All other legal males were defined as postrecruits. Because both fisheries are short, 15 d or less for most years, natural mortality during the fisheries can be ignored. The model links the postrecruits in year $t+1$ to the recruits, postrecruits, and catch in year t through natural mortality and catchability of the survey gear:

$$p_{t+1} = \left(p_t + r_t/\phi\right) e^{-M} - qC_t e^{-M\left(1-T_t\right)}, \qquad (1)$$

where p_t and r_t are relative abundances of postrecruits and recruits in year t, ϕ is the ratio of recruit catchability to postrecruit catchability, M is natural mortality, q is the survey catchability for postrecruit crabs, C_t is the commercial catch in year t, and T_t is the time lag from the survey to the midpoint of the fishery in year t. These relative abundances divided by the associated catchabilities are equal to corresponding absolute abundances of recruits and postrecruits by year. Thus, for given M and ϕ, the CSA model will estimate q; q and ϕ scale relative abundance to absolute abundance for the entire stock that occupies trawlable and untrawlable areas.

Parameter Estimation

We assumed that measurement errors of survey estimates of recruit and postrecruit relative abundances follow lognormal distribution. The maximum likelihood approach was used to estimate parameters. The log-likelihood function is proportional to

$$Log\_Li = -0.5n \ \log\left\{\sum_t \left[\left(\log(p_t + 0.001) - \log(\hat{p}_t + 0.001)\right)^2 + \left(\log(r_t + 0.001) - \log(\hat{r}_t + 0.001)\right)^2\right]\right\}, \qquad (2)$$

where n is the total number of observations and $\hat{p}_t$ and $\hat{r}_t$ are observed relative abundances of postrecruits and recruits in year t. Estimated parameters include natural mortality, catchability, recruits each year except the last, and postrecruits in the first year. Ideally, survey catchability or natural mortality would be estimated in advance by research studies. However, parameters for the Pribilof and St. Matthew Islands blue king crab stocks are uncertain. For this reason, we used 3 different approaches to estimate catchability and natural mortality because these parameters are confounded and difficult to estimate simultaneously. First, we assumed $q = 1$ and $\phi = 1$ and estimated M. Second, q was estimated for $M = 0.3$ and $\phi = 1$. Finally, a 2-phase approach (Otter Research Ltd. 1994) was used to estimate both q and M: (1) setting $q = 1$ and $\phi = 1$ and estimating M, and (2) estimating both q and M simultaneously for $\phi = 1$. To examine the relationships among q, ϕ, and M, we also estimated q for $\phi = 1$ and for fixed M ranging from 0.1 to 0.5 at intervals of 0.05, and we estimated q and M for fixed ϕ from 0.4 to 1.4 at intervals of 0.1.

Using AD Model Builder (Otter Research Ltd. 1994), we estimated parameters using the quasi-Newton method to minimize –1 times the likelihood values. The Builder provides a template-like approach to code generation and is very flexible and easy to use. It calculates standard deviations for all estimated parameters and any other desired values and calculates correlations among them. It also generates profile likelihood for any parameters or specified values. The software employs the C++ array language with automatic differentiation that should result in more stable optimization than less accurate derivative approximations (Otter Research Ltd. 1994).

RESULTS

The estimation algorithm converged quickly because of the model's simplicity and the small number of observed data points ($n = 34$). The results were quite robust in terms of sensitivity to the initial parameter values. For the Pribilof Islands blue king crab stock, setting $q = 1$ and $\phi = 1$ yielded a maximum likelihood estimate of M = 0.32; setting $M = 0.3$ and $\phi = 1$ resulted in an estimate of q = 1.40; and the 2-phase approach produced a combination of M = 0.16 and q = 1.98 (Table 1). The estimate of M with fixed $q = 1$ is lower than the fixed M value that produces $q = 1$; this may be due to insufficient years of catch data to estimate q for this stock. For the St. Matthew Island blue king crab stock, M = 0.29 when $q = 1$ and $\phi = 1$; q = 1.04 when $M = 0.3$ and $\phi = 1$; and the 2-phase approach estimated M = 0.18 and q = 1.23 (Table 1). The 2-phase approach resulted in the maximum logarithm of likelihood values for fixed $\phi = 1$ for both stocks.

The observed relative abundances of recruit, postrecruit, and all legal crabs were fitted well for both stocks (Figures 3, 4). The relative abundances, estimated by fixing $q = 1$ and $\phi = 1$ and the 2-phase approach, were almost identical for the St. Matthew Island stock and similar for the Pribilof Islands stock, except during the early 1980s and the mid 1990s. The 2-phase approach effected slightly higher relative abundances than those fixing $q = 1$ for the Pribilof Islands stock during the early 1980s and mid 1990s. The 95% confidence intervals were approximated by the profile likelihood. This method appears to underestimate the confidence intervals because >5% of the observed data points, or 8 out of 17 data points for the Pribilof Islands stock and 6 for the St. Matthew Island stock, are outside the limits (Figures 3, 4). Setting $q = 1$ for both stocks produced the highest absolute legal abundance estimates among the 3 approaches (Table 1).

The logarithms of likelihood values were a dome-shaped function of estimated natural mortality or postrecruit catchability for both stocks (Figure 5). As expected, natural mortality was negatively associated with postrecruit catchability. With $\phi = 1$, high log-likelihood values for the Pribilof Islands stock resulted from natural mortalities of 0.1–0.26 and postrecruit catchabilities of 1.49–2.24, and for the St. Matthew Island stock high log-likelihood values resulted from natural mortalities of 0.1–0.30 and postrecruit catchabilities of 1.04–1.36.

Table 1. Estimates and associated standard deviations (SD) of parameters and absolute legal crab abundance for a catch-survey analysis of Pribilof and St. Matthew Islands blue king crab stocks under 3 approaches. The ratio of recruit-to-postrecruit catchabilities was fixed at 1. Crab abundance is in millions of crabs. Log_Li is logarithm of likelihood, "NA" is not available, and q values corresponding to Log_q are in parentheses.

	Pribilof Islands						St. Matthew Island					
	Fixed $q=1$		Fixed $M=0.3$		2-phase		Fixed $q=1$		Fixed $M=0.3$		2-phase	
	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD
M	0.319	0.039	NA	NA	0.160	0.055	0.294	0.051	NA	NA	0.184	0.104
Log_q	NA	NA	0.334	0.140	0.683	0.156	NA	NA	0.043	0.088	0.203	0.156
			(1.40)		(1.98)				(1.04)		(1.23)	
Log_Li	-21.229	NA	-19.083	NA	-16.260	NA	-12.929	NA	-12.817	NA	-12.188	NA
Legals:												
1980	4.825	0.522	4.411	0.304	3.570	0.290	2.680	0.387	2.603	0.407	2.123	0.483
1981	2.951	0.302	2.576	0.201	2.089	0.164	3.501	0.347	3.419	0.382	2.979	0.454
1982	1.685	0.195	1.358	0.141	1.027	0.100	4.576	0.374	4.544	0.352	4.040	0.475
1983	1.043	0.136	0.763	0.115	0.514	0.076	3.129	0.209	3.099	0.206	2.815	0.265
1984	0.741	0.100	0.504	0.095	0.300	0.066	1.589	0.122	1.568	0.121	1.391	0.157
1985	0.662	0.072	0.468	0.075	0.304	0.055	0.961	0.086	0.940	0.092	0.818	0.111
1986	0.524	0.053	0.368	0.060	0.244	0.045	0.541	0.057	0.521	0.067	0.445	0.075
1987	0.415	0.041	0.291	0.048	0.206	0.035	0.845	0.114	0.818	0.124	0.686	0.138
1988	0.259	0.034	0.163	0.039	0.108	0.028	1.091	0.130	1.058	0.142	0.887	0.171
1989	0.188	0.029	0.121	0.029	0.092	0.021	1.555	0.193	1.504	0.213	1.224	0.268
1990	0.494	0.096	0.347	0.081	0.228	0.054	1.825	0.204	1.760	0.238	1.474	0.288
1991	1.014	0.174	0.717	0.151	0.456	0.105	2.403	0.261	2.330	0.293	1.942	0.370
1992	1.131	0.158	0.810	0.153	0.558	0.110	2.520	0.273	2.439	0.310	1.992	0.414
1993	1.199	0.151	0.866	0.155	0.636	0.109	2.648	0.270	2.555	0.323	2.123	0.416
1994	1.099	0.128	0.803	0.138	0.643	0.095	2.546	0.255	2.447	0.314	2.079	0.377
1995	1.184	0.145	0.875	0.149	0.725	0.101	2.312	0.257	2.209	0.315	1.884	0.359
1996	0.872	0.126	0.616	0.126	0.539	0.090	3.150	0.531	2.982	0.590	2.586	0.584

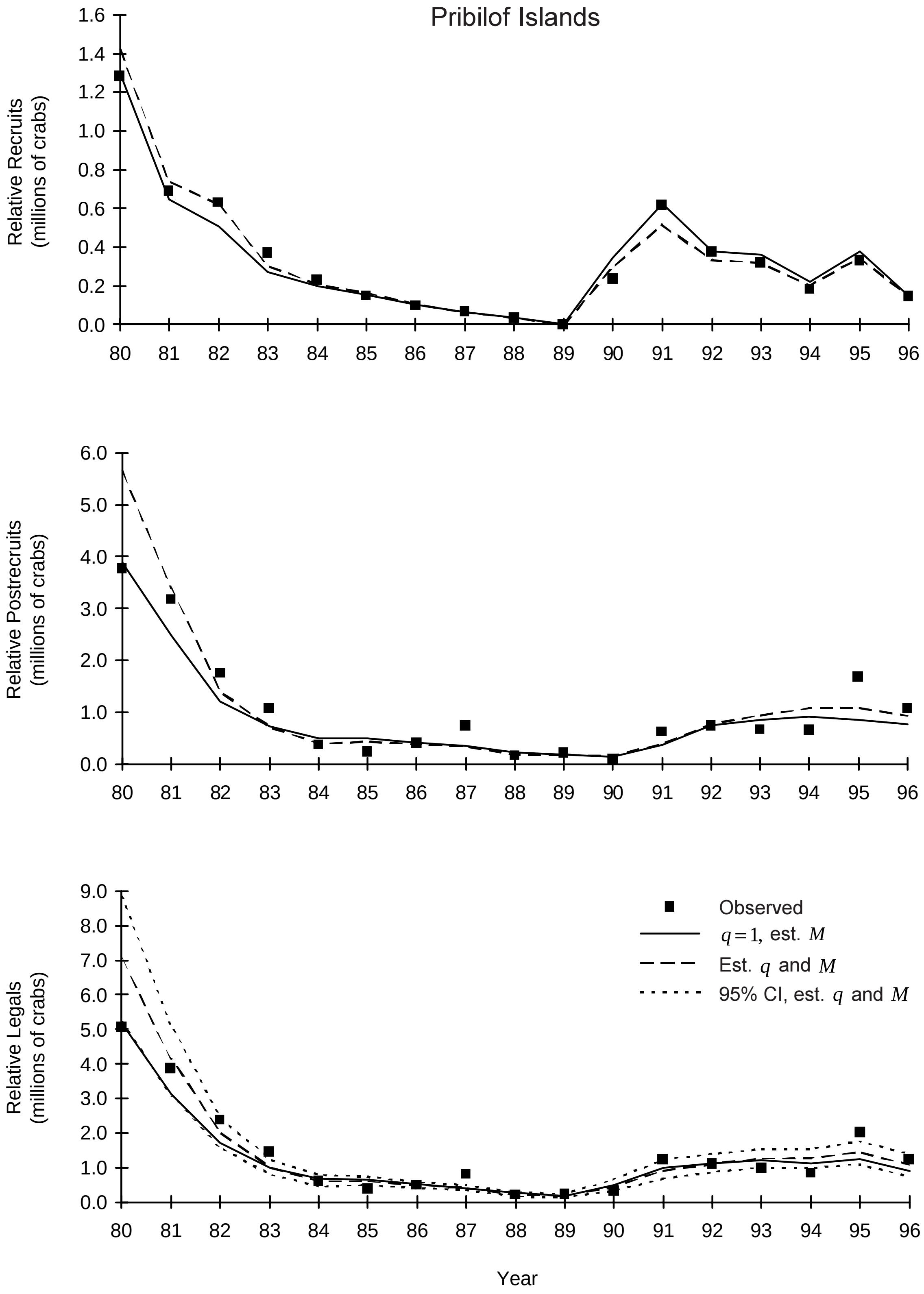

Figure 3. Comparisons of observed and estimated relative abundances of recruit, postrecruit, and legal blue king crabs in waters surrounding the Pribilof Islands. Solid lines denote results with q fixed at 1; dashed and dotted lines are results from the 2-phase approach.

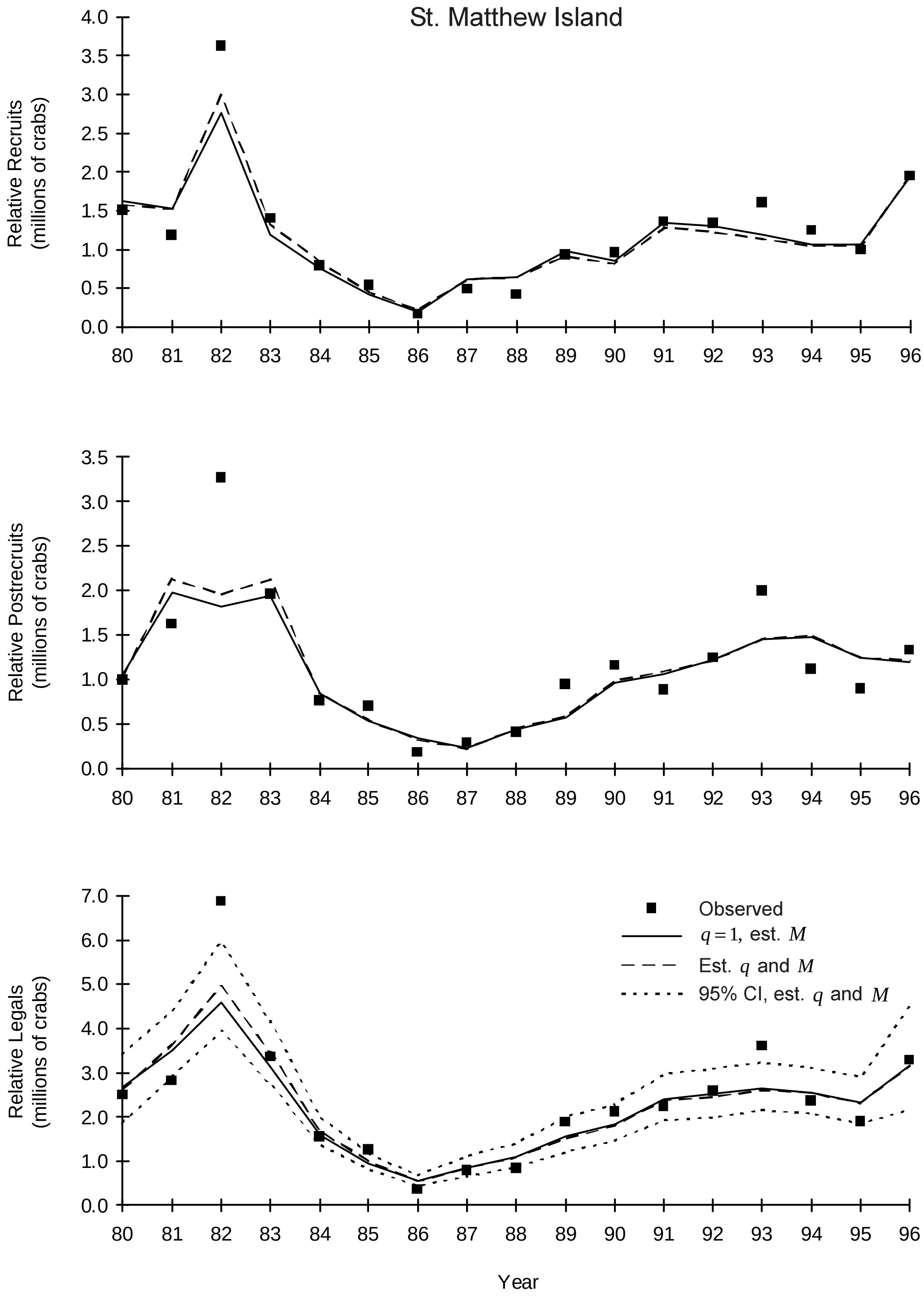

Figure 4. Comparisons of observed and estimated relative abundances of recruit, postrecruit, and legal blue king crabs in St. Matthew Island waters. Solid lines denote results with q fixed at 1; dashed and dotted lines are results from the 2-phase approach.

Estimates of natural mortality were also conditional on recruit catchability for both stocks (Figure 6). Decreased recruit catchability effected great increases in natural mortality but had moderate impact on postrecruit catchability. Therefore, we would underestimate natural mortality by assuming $\phi = 1$, if in fact, ϕ is <1. For both stocks the logarithms of likelihood values with $\phi < 1$ are similar to or higher than those with $\phi = 1$. From currently available data, we can reliably estimate only 1 out of 3 parameters (i.e., natural mortality, ratio of recruit-to-postrecruit catchabilities, and postrecruit catchability). However, based on the relationships among these 3 parameters (Figure 6) and a reasonable range of natural mortality (0.16–0.35) for both blue king crab stocks, postrecruit catchability probably is about 1.98–2.07 for the Pribilof Islands stock and about1.20–1.38 for the St. Matthew Island stock, and the ratios of recruit-to-postrecruit catchabilities for both stocks probably are <1.05.

Profile likelihood approximates the probability distribution of a parameter estimate. In Figures 7 and 8 we illustrate the profile likelihood for q and M estimated by fixing $\phi = 1$ and $q = 1$, $\phi = 1$ and M = 0.3, and the 2-phase approach. For either q or M, the distribution is much more spread out for the 2-phase approach than when fixing either q or M; we cannot reliably estimate these 2 parameters simultaneously.

With $\phi = 1$, estimates of absolute abundance and harvest rates depend on q. Estimates of absolute abundance were higher and harvest rates were lower for both stocks with fixed $q = 1$ than with q estimated from the 2-phase approach (Table 1; Figure 9). With M = 0.3, harvest rates for both stocks were higher than those with $q = 1$. With q estimated by the 2-phase approach, high harvest rates ranging from 0.42 to 0.57 occurred on the Pribilof Islands stock during the early 1980s. This was followed by light exploitation until 1987, when the harvest rate increased to 0.46; after that, the fishery was closed until 1995. Overall harvest rates were higher for the St. Matthew Island stock than for the Pribilof Islands stock. With q estimated by the 2-

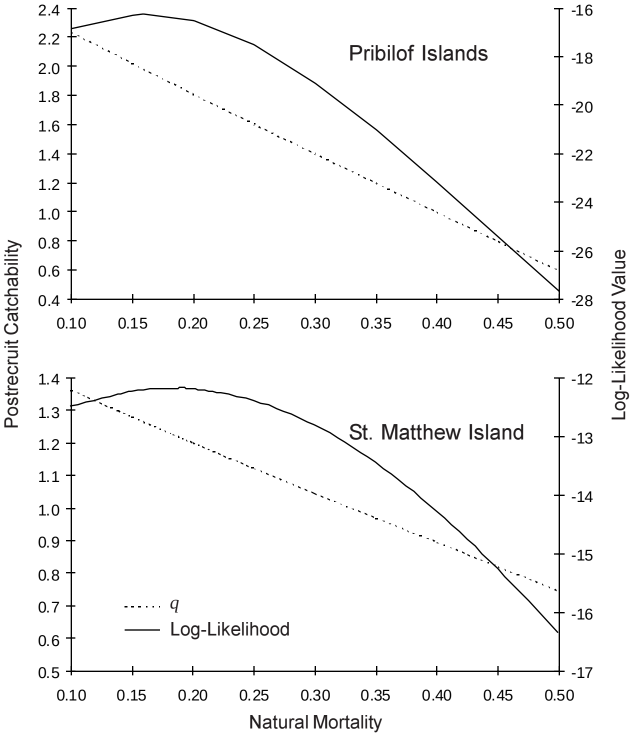

Figure 5. Relationships among postrecruit catchability, natural mortality, and log-likelihood values for the Pribilof and St. Matthew Islands blue king crab stocks from the catch-survey analysis with the ratio of recruit-to-postrecruit catchabilities = 1. Solid lines denote log-likelihood values and dotted lines represent postrecruit catchability.

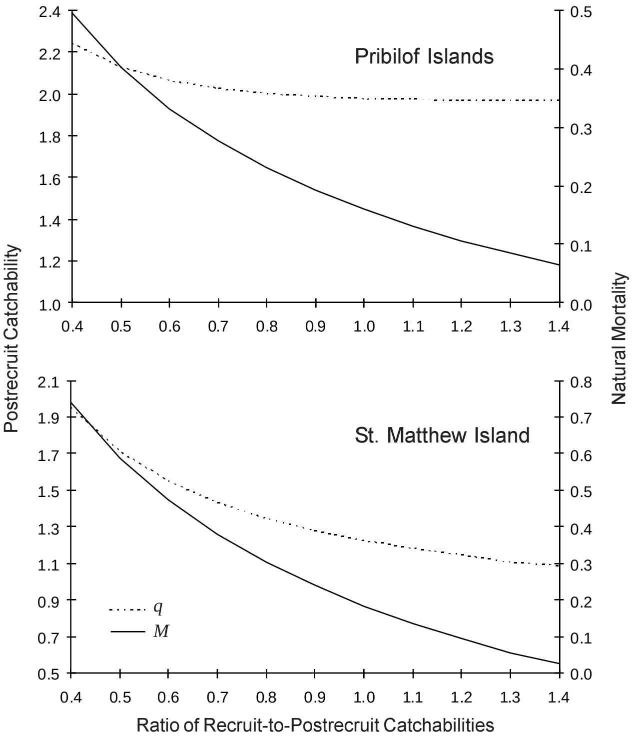

Figure 6. Relationships among postrecruit catchability, ratio of recruit-to-postrecruit catchabilities, and natural mortality for the Pribilof and St. Matthew Islands blue king crab stocks from the catch-survey analysis. Solid lines denote natural mortality and dotted lines represent postrecruit catchability.

phase approach, harvest rates at St. Matthew Island increased from 0.01 in 1980 to 0.69 in 1983, declined steadily to 0.20 in 1989, and fluctuated between 0.26 and 0.37 from 1990 to 1996.

DISCUSSION

The CSA provides much smoother annual estimates of legal blue king crab abundances for Pribilof and St. Matthew Islands stocks than direct estimates from the annual trawl survey. Residuals between estimated and observed abundances are relatively small for most years, which may result from small measurement errors for observed abundances. Also, the ratio of data points to parameters is small, 34:19 and 34:20, for each stock. Overfitting the observed data may occur, resulting in measurement errors greater than the residuals. However, because the estimated abundances are quite smooth and consistent from year to year, overfitting may not be too serious. One partial solution to overfitting is to expand the 2-stage model to include a third stage for prerecruit abundance (crabs with CL one growth increment below legal size). This expansion requires additional information on differences in growth and catchability between prerecruit and legal crabs. A 3-stage model would require estimation of an additional parameter but would add 50% more data points. This improvement would produce a model more similar to a length-based model (Zheng et al. 1995a, 1995b) than the 2-stage model.

Another drawback of the 2-stage CSA is that recruit abundance in the terminal year has to be set equal to the observed value because there are no other ob-

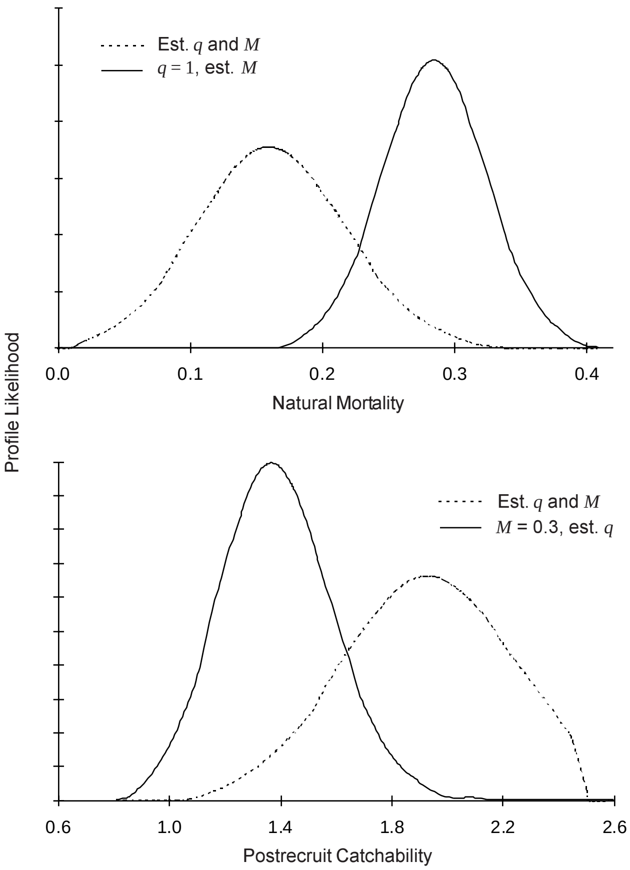

Figure 7. The profile likelihood for natural mortality and postrecruit catchability estimated by fixing the ratio of recruit-to-postrecruit catchabilities at 1 and natural mortality at 0.3, recruit and postrecruit catchabilities at 1, or by the 2-phase approach for the Pribilof Islands blue king crab stock.

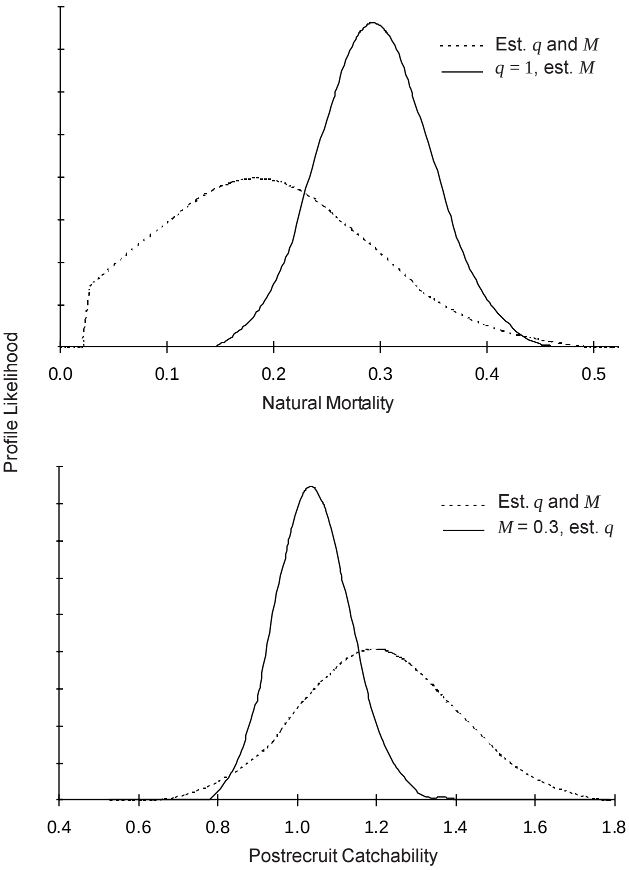

Figure 8. The profile likelihood for natural mortality and postrecruit catchability estimated by fixing the ratio of recruit-to-postrecruit catchabilities at 1 and natural mortality at 0.3, recruit and postrecruit catchabilities at 1, or by the 2-phase approach for the St. Matthew Island blue king crab stock.

servations upon which to assess measurement errors. As a result, the estimate of legal abundance in the terminal year may still contain a high level of survey measurement error. If a 3-stage model can be applied to these stocks, it would mitigate this problem by enabling estimation of recruit abundance and measurement error from previous year's prerecruit abundance and current year's recruit abundance.

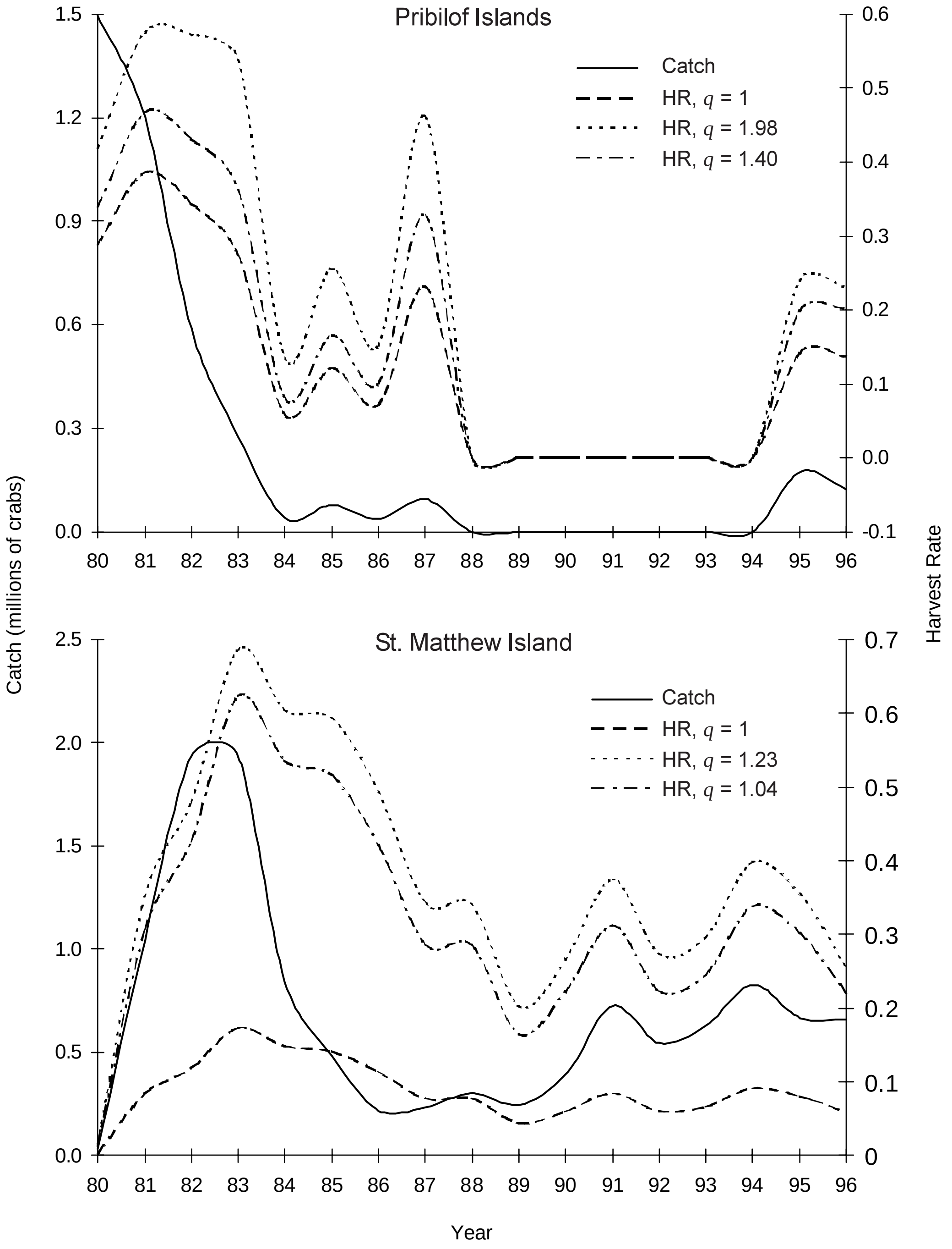

Figure 9. Time series of catches and harvest rates for the Pribilof and St. Matthew Islands blue king crab stocks with ratio of recruit-to-postrecruit catchability = 1. Dashed lines denote harvest rates estimated with *q* fixed at 1, dotted lines are harvest rates estimated from the 2-phase approach, and the combination of dotted and dashed lines represent harvest rates estimated with *M* fixed at 0.3.

High log-likelihood values were associated with survey catchability estimates of about 2 for the postrecruit Pribilof Islands stock and about 1.2 for the St. Matthew Island stock; these results were unexpected. We assumed the physical environment where blue king crabs live and grow is naturally similar for these 2 stocks, and we therefore assumed similar catchabilities.

A catchability <1 would be expected if untrawlable habitats have substantial numbers of crabs ignored in area expansions of trawl survey estimates, as can be inferred from the pot survey for the St. Matthew Island stock (Blau 1996). For the St. Matthew Island Section, commercial fishing is concentrated in the untrawlable area in most years (R. Morrison, Alaska Department of Fish and Game, personal communication), which also suggests that legal crab density in the untrawlable area may be higher than in the trawlable area. Furthermore, some crabs may escape capture by maneuvering away from the trawl or taking refuge in the cobble-gravel-rock substrate, resulting in a catchability of <1. If the catchability of blue king crabs is indeed <1, we may have underestimated natural mortality and absolute abundance. Natural mortality of 0.3 or higher would generate a catchability for legal crabs close to or under 1 when the ratio of recruit-to-postrecruit catchabilities is fixed at 1. From a mark-recapture study, natural mortality for Pribilof Islands blue king crabs was estimated at 0.21–1.02 for crabs 135–169 mm CL (Otto and Cummiskey 1990). The same calculations for St. Matthew Island blue king crabs yielded values ranging from 0.78 to 0.97 for crabs 120–134 mm CL. These estimates of natural mortality appear too high; the return rate of tagged crabs may have been underestimated due to tag loss, underreporting, and migration. By comparison, overall mean natural mortality for legal (≥135 mm CL) red king crabs in Bristol Bay of the eastern Bering Sea was estimated to be about 0.3 (Zheng et al. 1995a, 1995b). If natural mortality is indeed as high as those estimated by the tagging experiments, q will be much smaller than 1.

Catchability >1 would result if higher densities of legal crabs occurred in trawlable habitats than in untrawlable habitats. A positive bias in q would also result from process errors (Collie and Kruse *in press*); however, a bias of 80% rarely occurs. If the survey catchability is underestimated, then absolute abundance estimates of blue king crabs are inflated and harvest rates are higher than managers previously assumed. This effect would be much greater for the Pribilof Islands stock where the likely estimate of q is 1.98, compared to 1.23 for the St. Matthew Island stock. Based on these estimates of q, the actual harvest rates realized from the Pribilof Islands fishery were 0–58% of the legal male crabs, whereas rates for the St. Matthew Island fishery were 1–69% of the legal male crabs. These harvest rates exceeded the maximum rate of 60% (Pengilly and Schmidt 1995) occasionally and may also have been higher during some years than the legal harvest rates associated with the current 20% mature harvest rate strategy.

Catchability of blue king crabs from the trawl survey of the Pribilof Islands was not estimated as well as for St. Matthew Island, probably because of fewer years of catch data. The Pribilof Islands blue king crab fishery was closed from 1988 to 1994.

Changing catchability should not be problematic with fixed station locations and timing, which typifies the trawl survey (Shepherd 1988). However, blue king crabs molt biennially (Somerton and MacIntosh 1985; Jensen and Armstrong 1989), introducing complex spatial and temporal variation to assessments. Interannual changes in catchability may occur because of variability in environmental cues for mating and molting migrations. This could result in differing portions of the stock being surveyed between years or even differences between surveyed and commercially targeted portions of the stock. The fishing season for blue king crabs around the Pribilof Islands and St. Matthew Island has remained fairly consistent over time (Morrison et al. 1996). However, timing of molting may change, causing errors in classifying recruit and postrecruit crabs. A large bias in catchability could have occurred for the CSA model if errors in shell aging were large, if there was a difference in magnitude between recruits and postrecruits, or if aging errors were greatly asymmetric (Collie and Kruse *in press*).

Catchability of the trawl survey, used to estimate abundance and subsequent harvest levels, has implications for management. If the current harvest strategy is optimal for the current population abundance estimated by area-swept methods, then use of our lower population estimates corresponding to $q > 1$ for both blue king crab stocks will result in underharvest of the stock. Conversely, setting $M > 0.3$ makes $q < 1$ for St. Matthew Island blue king crab, thus generating higher population estimates, which if adopted, will effect overharvest of the stock. Unfortunately, only one pot survey has been conducted in a limited area near St. Matthew Island (Blau 1996) and none near the Pribilof Islands. Multiple years of pot surveys in both untrawlable and trawlable habitats accompanied by tagging studies would provide information germane to estimating natural mortality and trawl-survey catchability. The harvest strategy needs reevaluation when catchability is better known.

LITERATURE CITED

Alverson, D. L., and W. T. Pereyra. 1969. Demersal fish in the northeastern Pacific Ocean — an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. Journal of the Fisheries Research Board of Canada 26:1985–2001.

Blau, F. S. 1996. The 1995 St. Matthew Island blue king crab survey. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Regional Information Report 4K96-27, Kodiak.

Collie, J. S., and G. H. Kruse. *In press*. Estimating king crab abundance from commercial catch and research survey data. Canadian Special Publication of Fisheries and Aquatic Sciences 125, Ottawa.

Jensen, G. C., and D. A. Armstrong. 1989. Biennial reproductive cycle of blue king crab, *Paralithodes platypus*, at the Pribilof Islands, Alaska, and comparison to a cogener, *P. camtschatica*. Canadian Journal of Fisheries and Aquatic Sciences 46:932–940.

Kruse, G. H., and J. S. Collie. 1991. Preliminary application of a population size estimation model to the Bristol Bay stock of red king crabs. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Regional Information Report 5J91-09, Juneau.

Morrison, R., R. K. Gish, J. P. Cofske, and M. S. Schwenzfeirer. 1996. The commercial king and Tanner crab fisheries in the Bering Sea management area: a report to the Alaska Board of Fisheries. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Regional Information Report 4K96-9, Kodiak.

Otter Research Ltd. 1994. An introduction to AD Model Builder: for use in nonlinear modeling and statistics. Otter Research Ltd., Nanaimo, British Columbia.

Otto, R. S. 1981. Eastern Bering Sea crab fisheries. Pages 1037–1066 *in* D. W. Hood and J. A. Calder, editors. The eastern Bering Sea shelf: oceanography and resources, volume two. National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment, Seattle, Washington.

Otto, R. S. 1990. An overview of eastern Bering Sea king and Tanner crab fisheries. Pages 9–26 *in* Proceedings of the international symposium on king and Tanner crabs. University of Alaska Fairbanks, Alaska Sea Grant Program Report 90-4.

Otto, R. S., and P. A. Cummiskey. 1990. Growth of adult male blue king crab (*Paralithodes platypus*). Pages 245–258 *in* Proceedings of the international symposium on king and Tanner crabs. University of Alaska Fairbanks, Alaska Sea Grant Program Report 90-4.

Otto, R. S., R. A. MacIntosh, T. M. Armetta, and K. L. Stahl. 1981. Report to industry on the 1981 eastern Bering Sea crab survey. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest and Alaska Fisheries Center Processed Report 81-08, Kodiak, Alaska.

Paul, J. M., A. J. Paul, R. S. Otto, and R. A. MacIntosh. 1991. Spermatophore presence in relation to carapace length for eastern Bering Sea blue king crab (*Paralithodes platypus* (Brandt, 1850)) and red king crab (*P. camtschaticus* (Tilesius, 1815)). Journal of Shellfish Research 10:157–163.

Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof blue king crab. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Special Publication 7, Juneau.

Shepherd, J. G. 1988. Fish stock assessments and their data requirements. Pages 35–62 *in* J. A. Gulland, editor. Fish population dynamics, second edition. John Wiley and Sons, Ltd., New York.

Somerton, D.A., and R. A. MacIntosh. 1983. Weight-size relationships for three populations in Alaska of the blue king crab, *Paralithodes platypus* (Brandt, 1850) (Decapoda, Lithodidae). Crustaceana 45:169–175.

Somerton, D.A., and R. A. MacIntosh. 1985. The size at sexual maturity of blue king crab, *Paralithodes platypus*, in Alaska. Fishery Bulletin 81:621–628.

Stevens, B. G., J. A. Haaga, and R. A. MacIntosh. 1996. Report to industry on the 1995 eastern Bering Sea crab survey. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center Processed Report 96-01, Kodiak, Alaska.

Zheng, J., M. C. Murphy, and G. H. Kruse. 1995a. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 52:1229–1246.

Zheng, J., M. C. Murphy, and G. H. Kruse. 1995b. An update of the length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Alaska Fishery Research Bulletin 2(2):114–124.