Preliminary Application of a Population Size Estimation Model to the Bristol Bay Stock of Red King Crabs

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Abstract

This report serves as a discussion paper on preliminary application of a population size estimation model to the Bristol Bay stock of red king crabs. The report was written in an effort to seek inter-agency input into further model development and testing. Two versions of the model are applied: one that includes measurement error and process error, and the other which includes only measurement error. For demonstration purposes, these two models were fitted to survey and commercial catch data over 1975-1990. Instantaneous natural mortality was assumed to be constant, and equal to 0.3 in one set of model runs and 0.5 in another set.

The model produced encouraging results when applied to the Bristol Bay stock of red king crabs. There is a high degree of similarity between area-swept estimates of abundance and those derived from the population estimation model. Model estimates of abundance depend upon assumptions about mortality and error structure. In general, abundance estimates from trawl surveys were 18-27% higher than those estimated by the model with $M=0.3$. On the other hand, trawl survey estimates average 90-97% of model estimates when $M=0.5$.

Further model development and testing is desirable prior to possible implementation into the annual management process. For example, time trends in measurement and process error may indicate the need to alter the model's structure to include changes in mortality over time. We developed a draft work plan of tasks to be accomplished prior to possible implementation in the 1992 crab fisheries. When these analyses are completed, we expect to be able to provide annual estimates of abundance of harvestable red king crabs with estimates of variance based on integration of multiple years of survey assessments and commercial catches. The primary advantage of this population estimation model over area-swept estimates alone is that it provides a framework to integrate current year survey observations into a multi-year aggregate of fishery-independent (survey) and fishery-dependent (commercial catch) information on stock status.

Introduction

The goal of this study is to estimate population abundance of red king crabs *(Paralithodes camtschaticus)* in Bristol Bay, Alaska with the minimum bias and maximum precision possible with existing data. Specific objectives are to: (1) compute the magnitude of annual measurement errors in recruit and post-recruit components of the legal portion of the crab population that are derived from annual stock assessments; (2) estimate long-term average catchability coefficient for the trawl survey; and (3) calculate annual population abundance estimates for legal male red king crabs in Bristol Bay based upon methods that integrate multiple years of survey and commercial catch data.

This paper reports on progress toward these objectives, and is intended to foster interagency discussion on population assessments of king crabs in Alaska. Dialogue is sought regarding model structure, assumptions, use of input data, and on the choice of model parameters. Also, we hope that this document stimulates discussion on the subjects of measurement error, reliability of shell ageing methods, and methods of expansion of survey catches by area-swept and post-stratification procedures. All results should be considered very preliminary. We intend this progress report as a research discussion paper not a management decision document. The intended readership is crab fishery biologists, biometricians, and managers from the Alaska Department of Fish and Game (ADF&G) and National Marine Fisheries Service (NMFS). A more formal, peer-reviewed publication on this study is planned in the future.

NMFS has conducted multi-species trawl assessments of the Bering Sea annually since 1969 (except 1971). A brief overview of methods was presented by Otto (1986), and annual summaries of results are presented in reports, such as Stevens and MacIntosh (1990). Area-swept methods and stratified random sampling procedures are used to estimate annual abundance. To expand survey catches to population estimates, assumptions are made concerning the effective width of the trawl and the probability of capture of crabs given an encounter with the net. While the wing spread of the trawl has been measured since 1987 (Stevens and MacIntosh 1990), the effective width and capture rates are difficult to quantify. Both factors contribute, in part, to catchability coefficient.

As with any assessment, measurement error exists in survey estimates of crab abundance. These errors could result from non-random distribution of the population to be sampled, small sample sizes used to estimate size/age compositions of legal crabs for any one year, and other factors that may vary annually. Measurement errors are difficult to compute, because true abundance is unknown.

We applied a population estimation model to attempt to evaluate "bias" and "precision" of survey estimates of abundance. Bias results if the catchability coefficient of trawl gear was inadvertently over- or under-estimated in routine expansion of survey catches to the entire area occupied by the stock. Precision would be adversely affected if annual measurement errors were large with respect to population estimates. The model is a modified DeLury method of population size estimation originally developed by Collie and Sissenwine (1983) for application to groundfish stocks off New England. The method has been adapted for application to king crab populations in Alaska by Kruse (1986, 1987) and Collie (1991).

The M‹ ɹel

The model is based upon the following rela·ɩonship between the number of recruits, post-recruits, commercial catch, and natural mortality:

post-recruits	=	*legals*	-	*catch*	-	*nat. mort.*	(1)
[*next year*]		[*this year*]		[*this year*]		[*this year*]	

where legals comprise recruits and post-recruits. Note that this relationship involves data from two consecutive years. Thus, if there are τ years of survey data, then there are τ-1 equations. Recruits are defined as male crabs ≥135 mm carapace length (CL) and <150 mm CL with soft or new shell carapace condition, based on the conversion from legal size in terms of carapace width (165 mm CW) to carapace length (135 mm CL) and a mean growth increment of 15 mm (Otto 1986). Post-recruits are males in the same size range that are in the process of molting and those with old or very old shells, and all males of size ≥150 mm CL.

Eq. (1) can be expressed mathematically as follows:

$$P_{t+1} = (P_t + R_t)e^{(-M)} - C_t e^{(-M[1-T])} \qquad (2)$$

where P_t and R_t are the abundances (in numbers of crabs) of post-recruits and recruits in year t, C_t is the commercial catch in numbers of legal crabs, M is the instantaneous rate of natural mortality, and T is the proportion of the year that passes between the dates of the survey and the commercial fishery. In eq. (2) the number of legals this year $(P_t + R_t)$ is reduced by the natural mortality rate, and the commercial catch is discounted by the number of caught crabs that would have died due to annual natural mortality had they not been caught instead.

We could use eq. (2) to estimate M, given estimates of C_t from fish tickets (Griffin 1991) and estimates of abundance of P_{t+1}, P_t and R_t calculated from area-swept calculations of survey data (Otto 1986). In fact, this may be an interesting exercise. However, for purposes of this analysis, we chose to consider the area-swept estimates as measures of *relative abundance*. That is, we wish to estimate the catchability coefficient, q, used to scale survey catches to population abundance. Further, we desired to calculate estimate measurement error and process error. As discussed earlier, *measurement error* (also termed *observation error*) describes the way that annual survey estimates diverge from true estimates. *Process error* (also termed *equation error*) describes the way that the population dynamics model (eq. 2) may be structurally flawed due to factors such as temporal variability of M and non-linearity in the relationship between survey catches and true abundance.

We modified eq. (2) to allow us to treat the survey results as relative abundance, and to explicitly include process error ($e(t)$) and catchability coefficient. By substituting $p_t = qP_t$

and $r_t = qR_t$, we express relative abundance of post-recruits next year as:

$$p_{t+1} = (p_t + r_t)e^{(-M)} - qC_t e^{(-M[1-T])} + \epsilon(t) \tag{3}$$

where p_t and r_t are the "true" relative abundances of post-recruits and recruits in year t.

Because we assume that the survey measures relative abundance with error, we modify eq. (3) to include these measurement errors. To do so, we assume that measurement errors are log-normally distributed as follows:

$$\hat{p}_t = p_t e^{\eta_t} \tag{4}$$

and

$$\hat{r}_t = r_t e^{\delta_t} \tag{5}$$

where $\hat{p}_t$ and $\hat{r}_t$ are measured relative abundance, and η_t and δ_t are normally distributed.

Given $\hat{p}_t$, $\hat{r}_t$, and C_t for each year, we then solve for p_t , r_t , and q using non-linear least squares methods developed for the IBM-compatible microcomputer with a Microsoft FORTRAN Version 5.0 compiler and Version 1.1 of the IMSL library (primarily subroutine BCLSF). We estimate the number of legal crabs (in millions) as the sum of the number of recruits $(R_t = r_t/q)$ and post-recruits $(P_t = p_t/q)$. Because multiple years of data are included in the model, annual estimates of legal abundance constitute a "smoothed" time series that downplays effects of individual observations of recruits or post-recruits for any single year. Further, we attempt to evaluate "bias" by comparing estimates of q to unity, and "precision" of the survey by comparing $\hat{p}_t$ and $\hat{r}_t$ to the assumed "true" relative abundances, p_t and r_t. In fact, these are estimates of "bias" and "precision," because p_t and r_t are *estimated* and are not *known*.

Collie (1991) developed a version of this same model with measurement errors as defined in eqs. (4) and (5), but without process error $(\epsilon(t))$ as in eq. (3). Experience with similar population models suggests that it may be preferable to ignore process error when it cannot be estimated separately from measurement error (Collie 1991). We experimented with this alternative, "all observation error" version of the model here, as well.

Model Assumptions

The model is based on a number of assumptions, including the following:

1. The trawl survey results in estimates of *relative* abundance;

2. Instantaneous natural mortality rate is constant for recruits and post-recruits over 1975-1990, and can be estimated independently of the model;

3. Catchability coefficient is constant and independent of population abundance;

4. Measurement errors of recruits and post-recruits are independent and log-normally distributed;

5. For the mixed error model, the relative weights of measurement and process errors are known; and

6. Commercial catches are known without error.

Choice of Model Parameters

For the mixed error model, we assumed that the relative weights of measurement and process errors are equal. For the observation error model, process errors were assumed to be zero. The proportion of the year that passes between dates of the survey and dates of catches was assumed to be $T=0.25$. That is, we assumed that mean survey date was July 1 and mean catch date was October 1.

For purposes of discussion, we selected two estimates of M for separate model runs. First, we chose $M=0.3$ based, in part, upon the estimate used by the North Pacific Fishery Management Council (NPFMC 1990). Second, for illustrative purposes, we used an estimate, $M=0.5$, that happened to result in $q\approx 1$ for the "all observation error" model.

We assumed that survey estimates of recruit and post-recruit proportions of the legal population are more accurate than estimates based on catch samples. Survey samples are taken shortly after molting when errors in shell age determinations are likely to be smallest. On the other hand, estimates from commercial catches are generally based upon larger sample sizes.

Input Data to Model

Survey results for the Bristol Bay stock of red king crabs over 1975-1990 are summarized in Table 1. Estimates of abundance of legal male crabs were reported originally by Stevens and MacIntosh (1990). We are grateful to J. Reeves (NMFS, personal communication, Seattle) for providing survey data including length frequencies and carapace condition. Applying the size and carapace condition criteria described in ***The Model***, we estimated the numbers and proportions of recruit and post-recruit crabs in survey catches (Table 1).

Table 1. Survey catches and population estimates of legal red king crabs in Bristol Bay from NMFS trawl surveys. Survey catches are estimated, unadjusted raw catches of recruits and post-recruits. Recruits are defined as male crabs ≥135 mm carapace length (CL) and <150 mm CL with soft or new shell carapace condition. Post-recruits are all molting, old shell, or very old shell males in this same size range plus all males ≥150 mm CL. Abundance of legal male crabs are calculated from area-swept methods and random stratified sampling procedures, as reported by Stevens and MacIntosh (1990).

Year	Number		Proportion		Estimated Abundance (Millions of Legals)
	Recruits	Post-recruits	Recruits	Post-recruits	
1975	387	247	0.61	0.39	21.0
1976	648	513	0.56	0.44	32.7
1977	378	364	0.51	0.49	37.6
1978	821	629	0.57	0.43	46.6
1979	990	925	0.52	0.48	43.9
1980	535	501	0.52	0.48	36.1
1981	121	399	0.23	0.77	11.3
1982	61	70	0.47	0.53	4.7
1983	23	26	0.47	0.53	1.5
1984	97	46	0.68	0.32	3.1
1985	60	19	0.76	0.24	2.5
1986	337	77	0.81	0.19	5.9
1987	127	124	0.51	0.49	7.9
1988	490	360	0.58	0.42	6.4
1989	188	332	0.36	0.64	11.9
1990	112	228	0.33	0.67	9.2

Commercial catch data were reported by Griffin (1991), and are summarized in Table 2. Because estimates of catch weight are more accurate than catch numbers, we estimated catch numbers for each year as the total catch weight divided by average weight reported by Griffin (1991). Therefore, our estimates of catch numbers differ slightly from those reported in Griffin (1991).

Based upon survey (Table 1) and commercial catch data (Table 2) we constructed the set of input data for the model (Table 3). It includes estimated abundance of legal males separated into recruit and post-recruit components based on proportions of recruits and postrecruits in survey catches. The product of these proportions and legal abundance are the relative abundance estimates, $\hat{p}_t$ and $\hat{r}_t$. Commercial catch statistics are the same as those reported in Table 1.

Results

Mixed error model with M=0.3. In the first model run, we chose $M=0.3$ and fit the model described by eqs. (3), (4) and (5). Results are shown in Table 4. There are trends in the error estimates. Equation error tends to be positive prior to 1982 and negative thereafter. Model results suggest that true relative abundance of recruits may have been higher than that measured by the survey during 1975-1979 and that true relative abundance of post-recruits may have been lower during this same period, in general.

Estimates of abundance of legal crabs (Table 4) compares favorably with estimates from area-swept methods (Table 1), although the estimate of q indicates that area-swept estimates of abundance are generally 18% higher than estimates from the model. Area swept estimates tend to be significantly higher than model estimates during 1977-1982. Note that the model produced a higher estimate during 1988 and lower estimates during 1989-1990 compared to area-swept methods.

All observation error model with M=0.3. Results from the model with no process error for $M=0.3$ are shown in Table 5 and Figures 1-3. Note that the format of the computer printout for the observation error model differs somewhat from that of the mixed error model. As with the mixed error model, results indicate that true relative abundance of recruits may have been higher than that measured by the survey during 1975-1979 and that true relative abundance of post-recruits may have been lower during this same period (Figure 2).

Trends in errors are similar to those for the mixed error model. Because process error is excluded, measurement errors tend to be larger than for the mixed error model. Catchability $(q=1.27)$ is estimated to be higher than for the mixed error model; this suggests that, on average, estimates of abundance from area-swept methods are 27% higher than model estimates (Table 5, Figure 3). If these abundance estimates were correct, then the exploitation rate of legal males increased to 70-80% in 1980-1981 (Figure 1).

Table 2. Commercial catch data for red king crabs in Bristol Bay. Data were reported by Griffin (1991), except that commercial catch numbers are calculated from reported commercial catch weight and average weight. Because no commercial fishery was conducted in 1983, proportions and average weights for 1983 were calculated as averages of values for 1982 and 1984.

Year	Proportion		Commercial Catch		Ave. Weight
	Recruits	Post-recruits	No. (M crabs)	(M lbs)	(lbs)
1975	0.21	0.79	9.005	51.326	5.7
1976	0.56	0.44	10.653	63.920	6.0
1977	0.67	0.33	11.859	69.968	5.9
1978	0.75	0.25	15.107	87.618	5.8
1979	0.47	0.53	16.848	107.828	6.4
1980	0.44	0.56	20.959	129.948	6.2
1981	0.14	0.86	5.332	33.591	6.3
1982	0.68	0.32	0.536	3.001	5.6
1983	0.64	0.37	0.000	0.000	5.4
1984	0.59	0.41	0.804	4.182	5.2
1985	0.66	0.34	0.759	4.175	5.5
1986	0.65	0.35	2.110	11.394	5.4
1987	0.77	0.23	2.119	12.289	5.8
1988	0.59	0.41	1.231	7.388	6.0
1989	0.58	0.42	1.683	10.265	6.1
1990	0.49	0.51	3.133	20.362	6.5

Table 3. Model input data. Recruit and post-recruit estimates are treated as relative abundance measures, and are calculated as the product of proportions from survey catches times legal abundance estimates from Table 1. Commercial catch statistics come from Table 2.

Year	Relative Abundance		Commercial Catch (M crabs)	Average Weight (lbs)	Commercial Catch (M lbs)
	Recruits	Post-recruits			
1975	12.8	8.2	9.005	5.7	51.326
1976	18.3	14.4	10.653	6.0	63.920
1977	19.2	18.4	11.859	5.9	69.968
1978	26.4	20.2	15.107	5.8	87.618
1979	22.7	21.2	16.848	6.4	107.828
1980	18.6	17.5	20.959	6.2	129.948
1981	2.6	8.7	5.332	6.3	33.591
1982	2.2	2.5	0.536	5.6	3.001
1983	0.7	0.8	0.000	5.4	0.000
1984	2.1	1.0	0.804	5.2	4.182
1985	1.9	0.6	0.759	5.5	4.175
1986	4.8	1.1	2.110	5.4	11.394
1987	4.0	3.9	2.119	5.8	12.289
1988	3.7	2.7	1.231	6.0	7.388
1989	4.3	7.6	1.683	6.1	10.265
1990	3.0	6.2	3.133	6.5	20.362

Table 4. Estimates of abundance from the mixed error model with $M=0.3$.

ESTIMATED RELATIVE ABUNDANCE

YEAR	RECRUITS OBSERVED	RECRUITS ESTIMATED	RECRUITS RESIDUAL	RECRUITS EST SE	POST-RECRUITS OBSERVED	POST-RECRUITS ESTIMATED	POST-RECRUITS RESIDUAL	POST-RECRUITS EST SE	EQUATION ERROR
1975	12.800	17.891	-5.091	4.963	8.200	9.862	-1.662	3.476	
1976	18.300	23.593	-5.293	6.365	14.400	12.086	2.314	3.442	.025
1977	19.200	22.764	-3.564	6.687	18.400	16.391	2.009	4.385	.015
1978	26.400	28.852	-2.452	8.138	20.200	17.824	2.376	4.692	.010
1979	22.700	23.854	-1.154	7.289	21.200	20.324	.876	5.193	.004
1980	18.600	18.768	-.168	5.790	17.500	16.828	.672	4.190	.003
1981	2.600	2.357	.243	.861	8.700	6.589	2.111	1.284	.001
1982	2.200	1.338	.862	.447	2.500	1.539	.961	.474	-.056
1983	.700	.619	.081	.226	.800	1.125	-.325	.326	-.501
1984	2.100	1.468	.632	.443	1.000	1.025	-.025	.289	-.267
1985	1.900	1.836	.064	.540	.600	.760	-.160	.254	-.328
1986	4.800	5.906	-1.106	1.362	1.100	1.181	-.081	.371	-.025
1987	4.000	3.960	.040	1.213	3.900	3.306	.594	.928	.047
1988	3.700	5.100	-1.400	1.555	2.700	3.379	-.679	.913	-.003
1989	4.300	4.545	-.245	1.526	7.600	5.204	2.396	1.192	.085
1990	3.000	NA	NA	NA	6.200	5.650	.550	1.319	.016

ESTIMATES OF NUMBERS OF CRABS IN MILLIONS

P O P U L A T I O N   E S T I M A T E S
(point estimates and approx. 95% confidence intervals)

YEAR	RECRUITS LOWER	RECRUITS POINT	RECRUITS UPPER	POST-RECRUITS LOWER	POST-RECRUITS POINT	POST-RECRUITS UPPER	LEGALS POINT	COMMERCIAL CATCH	NATURAL DEATHS
1975	.000	15.136	59.880	.000	8.344	30.343	23.480	9.005	4.271
1976	.000	19.960	93.454	.000	10.225	31.992	30.185	10.653	5.677
1977	.000	19.259	100.368	.000	13.867	49.053	33.127	11.859	6.196
1978	.000	24.409	144.427	.000	15.080	55.357	39.489	15.107	7.191
1979	.000	20.181	116.381	.000	17.195	66.350	37.375	16.848	6.292
1980	.000	15.878	76.329	.000	14.237	46.217	30.116	20.959	3.583
1981	.652	1.994	3.336	2.819	5.575	8.331	7.569	5.332	.887
1982	.697	1.132	1.567	.692	1.302	1.912	2.434	.536	.523
1983	.350	.524	.697	.568	.952	1.336	1.476	.000	.382
1984	.819	1.242	1.666	.577	.867	1.157	2.109	.804	.385
1985	.939	1.553	2.167	.399	.643	.887	2.196	.759	.416
1986	1.591	4.997	8.402	.571	.999	1.427	5.996	2.110	1.129
1987	.628	3.350	6.072	1.008	2.797	4.587	6.147	2.119	1.166
1988	.000	4.315	8.801	1.007	2.859	4.710	7.174	1.231	1.611
1989	.000	3.845	8.178	1.407	4.403	7.399	8.248	1.683	1.799
1990	NA	2.538	NA	1.141	4.780	8.419	7.318	3.133	1.266

Table 4. Continued.

ESTIMATES OF MILLIONS OF POUNDS OF CRABS

POPULATION ESTIMATES
(point estimates and approx. 95% confidence intervals)

YEAR	RECRUITS LOWER	RECRUITS POINT	RECRUITS UPPER	LEGALS LOWER	LEGALS POINT	LEGALS UPPER	COMMERCIAL CATCH	NATURAL DEATHS
1975				.000	133.835	418.035	51.326	24.346
1976				.000	181.110	641.009	63.920	34.062
1977				.000	195.447	717.080	69.968	36.559
1978				.000	229.037	963.294	87.618	41.708
1979				.000	239.202	930.603	107.828	40.271
1980				.000	186.718	610.729	129.948	22.212
1981				28.374	47.686	66.998	33.591	5.591
1982				9.437	13.633	17.828	3.001	2.929
1983				5.695	7.969	10.243	.000	2.065
1984				8.300	10.969	13.638	4.182	2.001
1985				8.445	12.078	15.711	4.175	2.289
1986				13.846	32.378	50.911	11.394	6.096
1987				16.757	35.653	54.548	12.289	6.764
1988				13.921	43.041	72.161	7.388	9.667
1989				18.180	50.313	82.446	10.265	10.972
1990				23.917	47.569	71.221	20.362	8.226

ESTIMATES OF THOUSANDS OF METRIC TONS OF CRABS

POPULATION ESTIMATES
(point estimates and approx. 95% confidence intervals)

YEAR	RECRUITS LOWER	RECRUITS POINT	RECRUITS UPPER	LEGALS LOWER	LEGALS POINT	LEGALS UPPER	COMMERCIAL CATCH	NATURAL DEATHS
1975				.000	60.707	189.619	23.281	11.043
1976				.000	82.151	290.760	28.994	15.450
1977				.000	88.654	325.265	31.737	16.583
1978				.000	103.890	436.947	39.743	18.919
1979				.000	108.501	422.119	48.910	18.267
1980				.000	84.695	277.025	58.944	10.075
1981				12.870	21.630	30.390	15.237	2.536
1982				4.281	6.184	8.087	1.361	1.328
1983				2.583	3.615	4.646	.000	.937
1984				3.765	4.975	6.186	1.897	.907
1985				3.830	5.479	7.127	1.894	1.038
1986				6.280	14.687	23.093	5.168	2.765
1987				7.601	16.172	24.743	5.574	3.068
1988				6.314	19.523	32.732	3.351	4.385
1989				8.246	22.822	37.397	4.656	4.977
1990				10.849	21.577	32.306	9.236	3.731

Table 4. Continued.

PARAMETER SUMMARY

NUMBER OF YEARS = 16

NUMBER OF AGE CLASSES = 2

NUMBER OF RESIDUAL ERRORS = 46, AS FOLLOWS:

15 FOR RECRUIT MEASUREMENT ERRORS (ALL YEARS BUT LAST),
16 FOR POST-RECRUIT MEASUREMENT ERRORS (ONE EACH YEAR),
15 FOR EQUATION ERRORS (ONE FOR EACH EQUATION)

NUMBER OF PARAMETERS TO BE ESTIMATED = 32, AS FOLLOWS:

ONE FOR TRUE POST-RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR,
ONE FOR TRUE RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR
(EXCEPT THE LAST YEAR), AND ONE FOR Q.

DEGREES OF FREEDOM = 14 (NO. OF RESIDUALS MINUS NO. OF PARAMETERS)

PARAMETERS ESTIMATED INDEPENDENT OF MODEL

RECRUIT CATCHABILITY = 1.00 TIMES ADULT CATCHABILITY

COMMERCIAL CATCH OCCURS 3.0 MONTHS AFTER SURVEY

INSTANTANEOUS NATURAL MORTALITY = .3

RELATIVE ERROR WEIGHTS

EQUATION ERROR	1.00
RECRUIT OBSERVATION ERROR	1.00
LEGAL OBSERVATION ERROR	1.00

NON-LINEAR LEAST-SQUARES FIT

NUMBER OF ITERATIONS = 9

NUMBER OF FUNCTION EVALUATIONS = 10

SUM OF SQUARES = 2.03

CATCHABILITY COEFFICIENT (X10**-6)

INITIAL GUESS	1.00000	
FINAL ESTIMATE	1.18199	
95% CONFIDENCE INTERVAL (	.82342,	1.54056)
ESTIMATED STANDARD ERROR	.16717	

Table 5. Estimates of abundance from the me .surement error model with $M=0.3$.

ESTIMATED RELATIVE ABUNDANCE

	RECRUITS				POST-RECRUITS			
YEAR	OBSERVED	ESTIMATED	RESIDUAL	EST SE	OBSERVED	ESTIMATED	RESIDUAL	EST SE
1975	12.800	18.543	-5.743	.021	8.200	10.020	-1.820	.553
1976	18.300	24.615	-6.315	.224	14.400	12.032	2.368	NA
1977	19.200	23.806	-4.606	.354	18.400	16.351	2.049	NA
1978	26.400	30.555	-4.155	.359	20.200	17.728	2.472	NA
1979	22.700	25.608	-2.908	.443	21.200	20.456	.744	NA
1980	18.600	20.527	-1.927	.543	17.500	17.048	.452	NA
1981	2.600	2.389	.211	.655	8.700	6.591	2.109	NA
1982	2.200	1.118	1.082	.925	2.500	1.248	1.252	NA
1983	.700	.541	.159	.828	.800	1.210	-.410	NA
1984	2.100	1.225	.875	.682	1.000	1.297	-.297	NA
1985	1.900	1.715	.185	1.649	.600	1.054	-.454	NA
1986	4.800	6.085	-1.285	1.396	1.100	1.282	-.182	NA
1987	4.000	4.066	-.066	.591	3.900	3.319	.581	NA
1988	3.700	5.300	-1.600	.529	2.700	3.323	-.623	NA
1989	4.300	4.619	-.319	.516	7.600	5.140	2.460	NA
1990	3.000	NA	NA	NA	6.200	5.524	.676	NA

P O P U L A T I O N   E S T I M A T E S

NUMBERS OF CRABS IN MILLIONS

YEAR	RECRUITS	POST-RECRUITS	LEGALS	COMMERCIAL CATCH	NATURAL DEATHS	LEGAL POUNDS	BIOMASS TONS
1975	14.608	7.893	22.501	9.005	4.018	128.257	58.177
1976	19.391	9.479	28.870	10.653	5.336	173.220	78.572
1977	18.754	12.881	31.635	11.859	5.810	186.645	84.662
1978	24.071	13.966	38.037	15.107	6.815	220.613	100.070
1979	20.174	16.115	36.289	16.848	6.011	232.248	105.347
1980	16.170	13.430	29.600	20.959	3.449	183.523	83.245
1981	1.882	5.192	7.075	5.332	.759	44.570	20.217
1982	.881	.983	1.864	.536	.375	10.440	4.736
1983	.426	.953	1.380	.000	.358	7.449	3.379
1984	.965	1.022	1.987	.804	.353	10.333	4.687
1985	1.351	.830	2.181	.759	.412	11.998	5.442
1986	4.793	1.010	5.803	2.110	1.079	31.338	14.215
1987	3.203	2.614	5.817	2.119	1.081	33.740	15.304
1988	4.176	2.617	6.793	1.231	1.513	40.758	18.488
1989	3.639	4.049	7.688	1.683	1.654	46.897	21.272
1990	2.363	4.352	6.715	3.133	1.109	43.647	19.798

Table 5. Continued.

```
        PARAMETER SUMMARY

NUMBER OF YEARS = 16

NUMBER OF AGE CLASSES =  2

NUMBER OF RESIDUAL ERRORS = 31, AS FOLLOWS:

        15 FOR RECRUIT MEASUREMENT ERRORS (ALL YEARS BUT LAST),
        16 FOR POST-RECRUIT MEASUREMENT ERRORS (ONE EACH YEAR),

NUMBER OF PARAMETERS TO BE ESTIMATED = 17, AS FOLLOWS:

        ONE FOR TRUE POST-RECRUIT RELATIVE ABUNDANCE IN FIRST YEAR,
        ONE FOR TRUE RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR
        (EXCEPT THE LAST YEAR), AND ONE FOR Q.

DEGREES OF FREEDOM = 14 (NO. OF RESIDUALS MINUS NO. OF PARAMETERS)

         PARAMETERS ESTIMATED INDEPENDENT OF MODEL

RECRUIT CATCHABILITY =  1.00 TIMES ADULT CATCHABILITY

COMMERCIAL CATCH OCCURS   3.0 MONTHS AFTER SURVEY

INSTANTANEOUS NATURAL MORTALITY =  .3


                  RELATIVE ERROR WEIGHTS

RECRUIT OBSERVATION ERROR        1.00
POST-RECRUIT OBSERVATION ERROR   1.00


         NON-LINEAR LEAST-SQUARES FIT

NUMBER OF ITERATIONS =            14

NUMBER OF FUNCTION EVALUATIONS = 260

SUM OF SQUARES = 2.816


             CATCHABILITY COEFFICIENT (X10**-6)

INITIAL GUESS                1.00000
FINAL ESTIMATE               1.26940
95% CONFIDENCE INTERVAL (     .11435,  2.42444)
ESTIMATED STANDARD ERROR      .53848
```

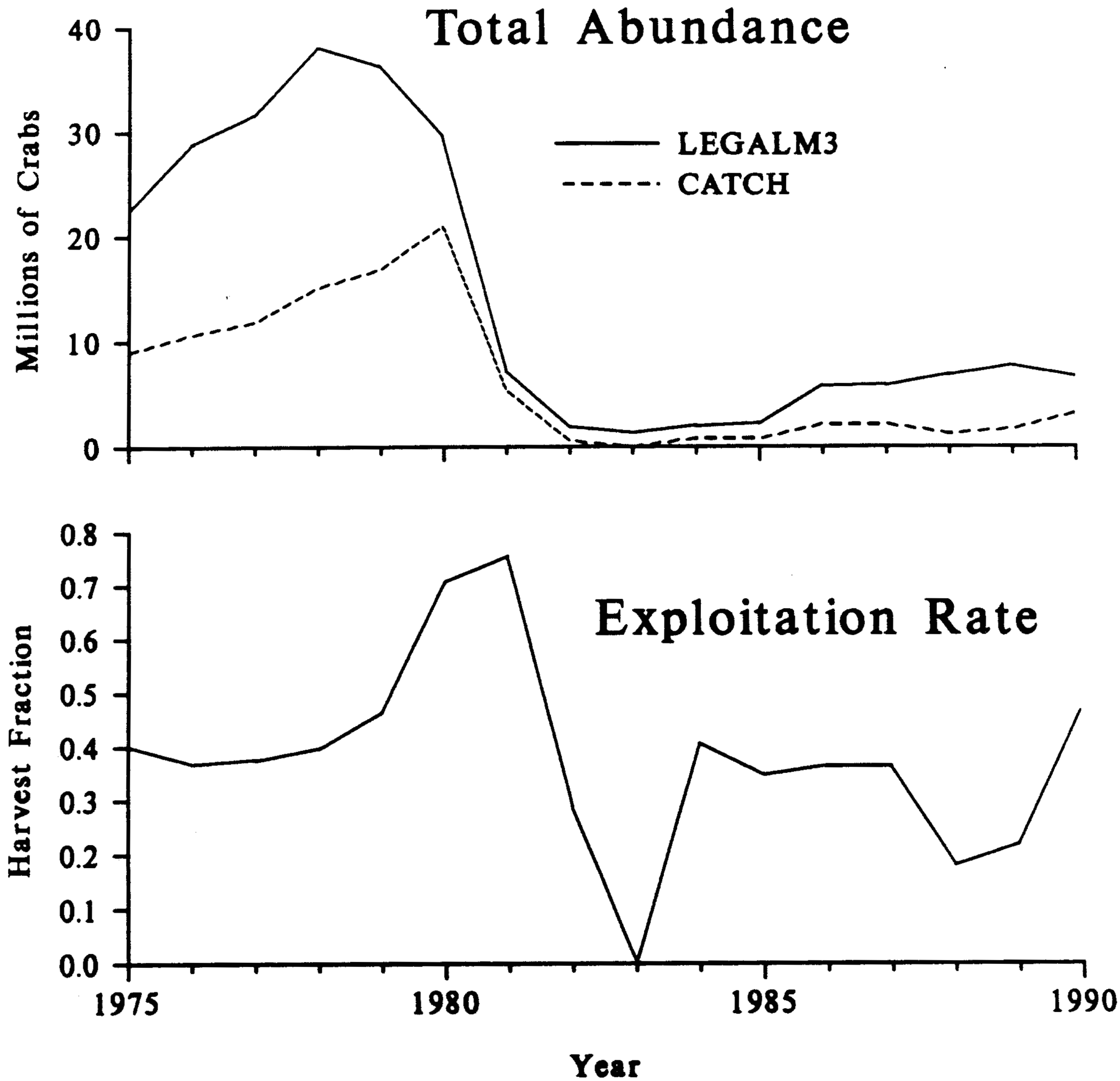

Figure 1. Commercial catch, estimated abundance of legal crabs (upper panel), and estimated exploitation rate (lower panel) from the observation error model with M=0.3 for Bristol Bay red king crabs over 1975-1990.

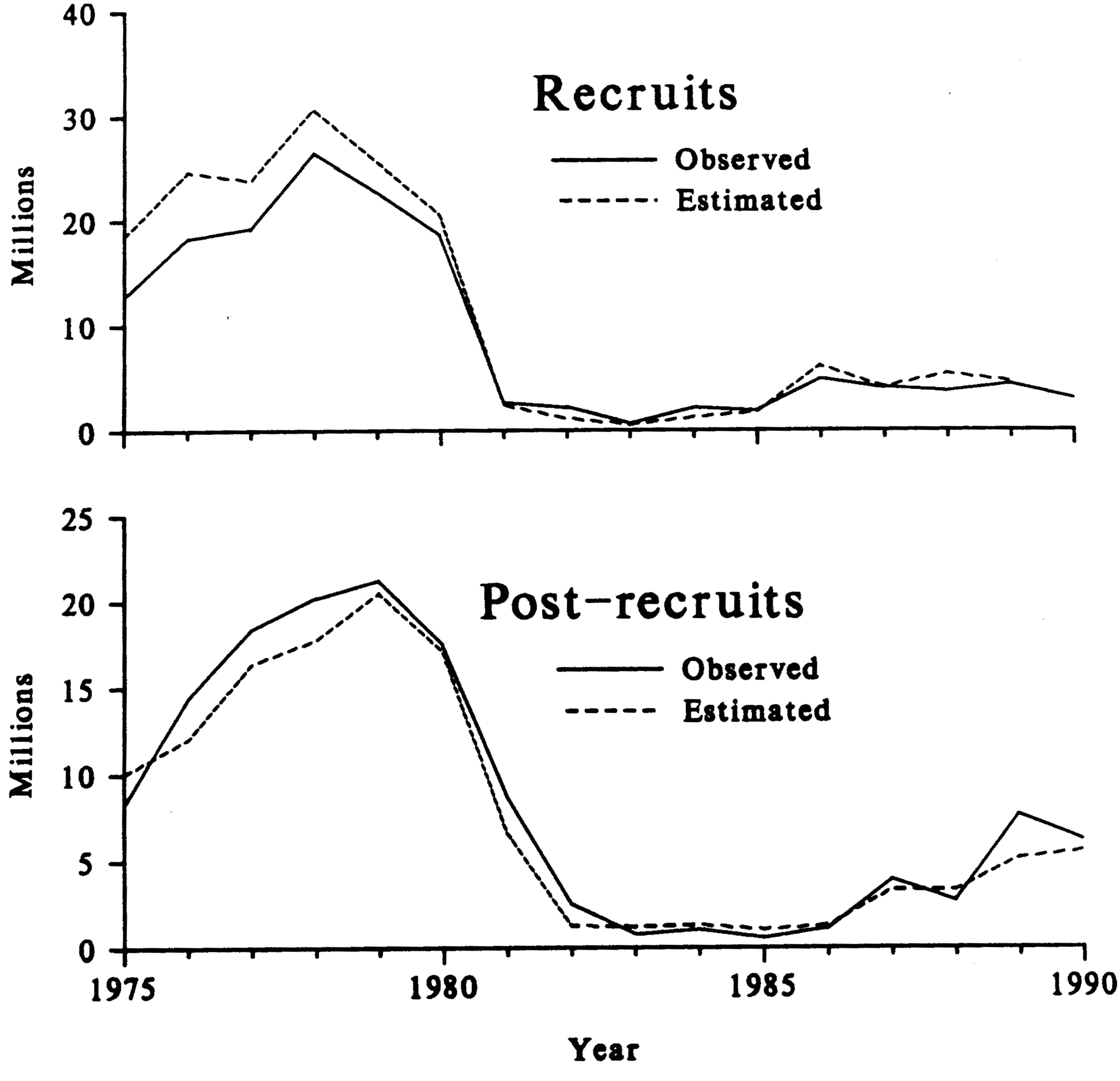

Figure 2. Observed and estimated abundance of recruit (upper panel) and post-recruit (lower panel) red king crabs from Bristol Bay over 1975-1990 from the observation error model with M=0.3.

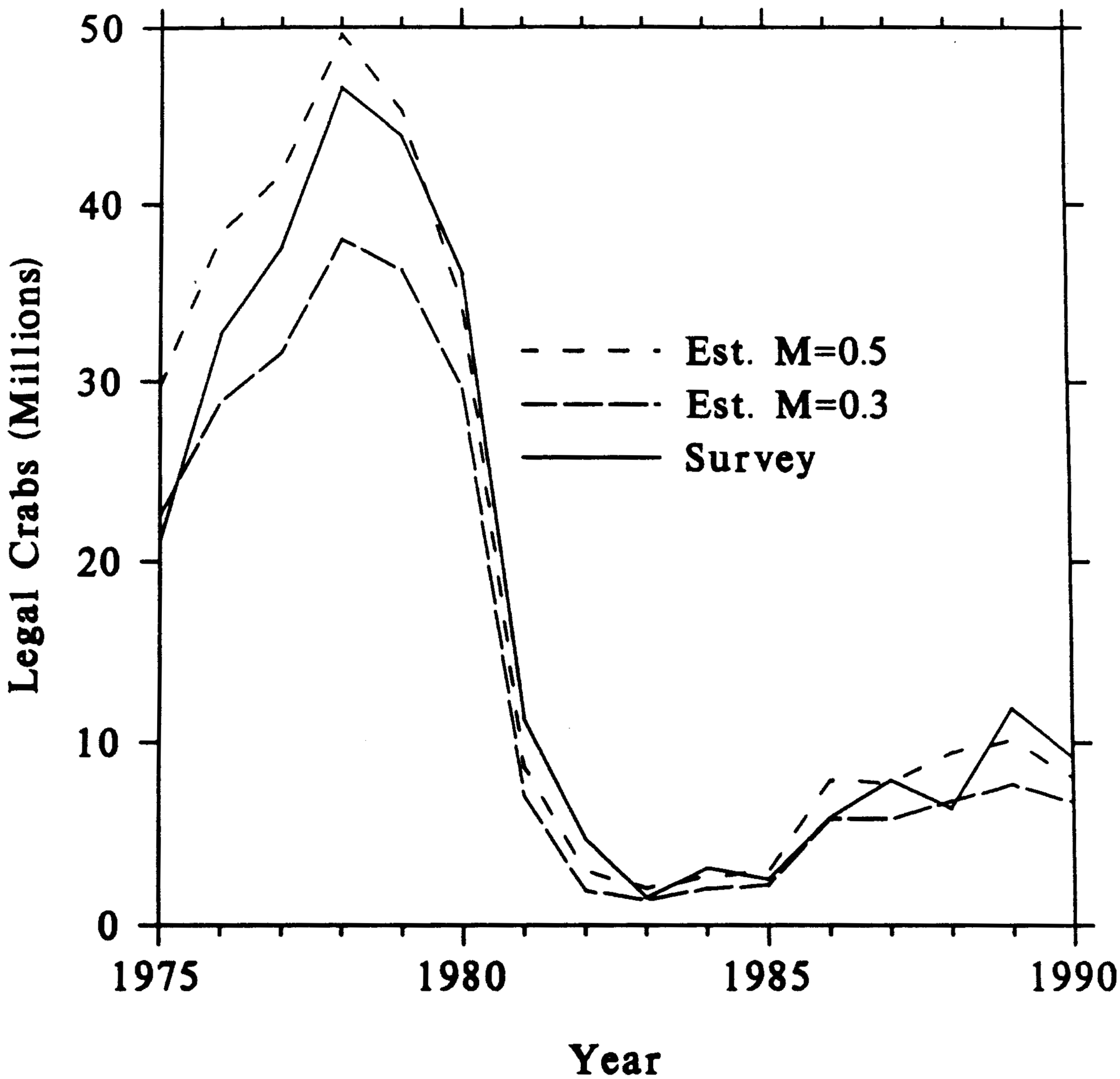

Figure 3. Estimated abundance of legal red king crabs in Bristol Bay over 1975-1990 from area-swept survey estimates (Stevens and MacIntosh 1990), and estimates from the observation error model with M=0.3 and M=0.5.

Mixed error model with $M = 0.5$. Results from the mixed error model for $M = 0.5$ are shown in Table 6. The same patterns in measurement errors occur as with the other model runs with $M = 0.3$. In comparison with results with $M = 0.3$, a primary difference is the estimate of a lower catchability coefficient, $q = 0.9$. That is, survey estimates of legal abundance are approximately 10% below model estimates of abundance with the mixed error model and $M = 0.5$. Estimates of abundance from this model (Table 6) are higher than area-swept estimates (Table 1) during 1975-1979 and 1986-1988.

All observation error model with $M = 0.5$. Results from the measurement error model for $M = 0.5$ are shown in Table 7 and Figure 3. Estimated relative abundance of recruits and post-recruits compares favorably with estimates from other model runs. For this model, catchability coefficient is approximately unity ($q = 0.97$). This version of the model resulted in estimates of legal abundance greater than those based on area-swept methods for 1975-1979, 1983, 1985-1986, and 1988 (Figure 3).

Discussion

There is general agreement between estimates of legal male red king crabs in Bristol Bay as estimated by our population estimation model and as estimated by area-swept, random stratified methods. All model runs suggest an increase in abundance of legals from 1975 to 1978, a drastic decline through 1983, and a modest recovery to 1990. However, the actual abundance levels vary among the model trials.

There is a tradeoff between instantaneous natural mortality and catchability coefficient. If the assumed rate of natural mortality ($M = 0.3$) by NPFMC (1990) is typical, then preliminary model results suggest that area-swept estimates of abundance tend to be larger than model-based estimates of abundance on average. Conversely, higher rates of natural mortality ($M \approx 0.5$) are required to equate area-swept and model-based estimates of abundance on average.

Trends in process and measurement errors may suggest some flaws in model structure. Relative abundance estimates are very similar for the mixed error model and observation error model with $M = 0.3$ and $M = 0.5$. For the mixed error model for both $M = 0.3$ and $M = 0.5$, process error tended to be positive during 1975-1980, negative during 1981-1985, and positive during 1986-1990. In all four instances investigated in this report, the model tended to result in higher estimates of recruits than those measured by surveys during 1975-1979. Also, it tended to result in lower estimates of post-recruits during this same period. The converse (lowered recruits and raised post-recruits) tended to occur during the mid-1980's. It is possible that shifts in M, such as those suggested by Matulich et al. (1988) and others, could result in these error structures.

Our model tends to smooth annual estimates of abundance by estimating "best fits" to survey data of recruits and post-recruits from adjacent years. For example, based on model

Table 6. Estimates of abundance from the mixed error model with $M=0.5$.

ESTIMATED RELATIVE ABUNDANCE

	RECRUITS				POST-RECRUITS				EQUATION
YEAR	OBSERVED	ESTIMATED	RESIDUAL	EST SE	OBSERVED	ESTIMATED	RESIDUAL	EST SE	ERROR
1975	12.800	18.177	-5.377	5.413	8.200	9.932	-1.732	3.635	
1976	18.300	24.905	-6.605	7.093	14.400	11.513	2.887	3.239	.032
1977	19.200	24.107	-4.907	7.358	18.400	15.521	2.879	4.165	.020
1978	26.400	29.988	-3.588	8.855	20.200	16.718	3.482	4.379	.016
1979	22.700	23.358	-.658	7.508	21.200	18.994	2.206	4.861	.007
1980	18.600	16.588	2.012	5.530	17.500	15.272	2.228	3.742	.002
1981	2.600	2.265	.335	.856	8.700	6.353	2.347	1.325	-.011
1982	2.200	1.475	.725	.520	2.500	1.830	.670	.569	-.100
1983	.700	.656	.044	.248	.800	1.227	-.427	.359	-.446
1984	2.100	1.576	.524	.504	1.000	.981	.019	.288	-.162
1985	1.900	1.908	-.008	.604	.600	.754	-.154	.257	-.300
1986	4.800	6.235	-1.435	1.593	1.100	1.149	-.049	.363	.004
1987	4.000	4.213	-.213	1.351	3.900	3.243	.657	.921	.069
1988	3.700	5.708	-2.008	1.794	2.700	3.232	-.532	.865	.020
1989	4.300	4.956	-.656	1.693	7.600	4.787	2.813	1.126	.125
1990	3.000	NA	NA	NA	6.200	4.916	1.284	1.160	.047

ESTIMATES OF NUMBERS OF CRABS IN MILLIONS

P O P U L A T I O N   E S T I M A T E S
(point estimates and approx. 95% confidence intervals)

	RECRUITS			POST-RECRUITS			LEGALS	COMMERCIAL	NATURAL
YEAR	LOWER	POINT	UPPER	LOWER	POINT	UPPER	POINT	CATCH	DEATHS
1975	.000	20.203	90.244	.000	11.040	42.728	31.243	9.005	9.477
1976	.000	27.682	147.740	.000	12.796	38.378	40.478	10.653	12.595
1977	.000	26.794	155.921	.000	17.252	59.242	44.046	11.859	13.622
1978	.000	33.331	220.146	.000	18.582	64.968	51.914	15.107	15.702
1979	.000	25.962	160.054	.000	21.112	77.935	47.074	16.848	13.254
1980	.000	18.438	90.777	.000	16.975	50.685	35.413	20.959	7.380
1981	.751	2.518	4.284	2.781	7.061	11.341	9.579	5.332	2.102
1982	.849	1.640	2.431	.776	2.034	3.291	3.674	.536	1.278
1983	.430	.729	1.028	.679	1.364	2.049	2.093	.000	.824
1984	.966	1.752	2.538	.634	1.090	1.546	2.842	.804	.867
1985	1.042	2.121	3.201	.459	.838	1.217	2.959	.759	.927
1986	.655	6.930	13.205	.653	1.277	1.902	8.207	2.110	2.570
1987	.153	4.683	9.212	1.121	3.605	6.088	8.287	2.119	2.598
1988	.000	6.345	14.263	1.180	3.593	6.006	9.937	1.231	3.525
1989	.000	5.508	12.579	1.564	5.320	9.076	10.829	1.683	3.734
1990	NA	3.334	NA	1.434	5.464	9.493	8.798	3.133	2.482

Table 6. Continued.

ESTIMATES OF MILLIONS OF POUNDS OF CRABS

POPULATION ESTIMATES
(point estimates and approx. 95% confidence intervals)

	RECRUITS			LEGALS			COMMERCIAL	NATURAL
YEAR	LOWER	POINT	UPPER	LOWER	POINT	UPPER	CATCH	DEATHS
1975				.000	178.086	616.279	51.326	54.020
1976				.000	242.866	979.386	63.920	75.573
1977				.000	259.874	1060.989	69.968	80.373
1978				.000	301.100	1417.525	87.618	91.074
1979				.000	301.275	1233.339	107.828	84.824
1980				.000	219.558	714.368	129.948	45.754
1981				31.177	60.347	89.516	33.591	13.240
1982				12.252	20.573	28.893	3.001	7.156
1983				7.266	11.304	15.342	.000	4.448
1984				10.052	14.778	19.504	4.182	4.507
1985				9.982	16.276	22.570	4.175	5.099
1986				10.270	44.320	78.371	11.394	13.876
1987				18.106	48.067	78.028	12.289	15.070
1988				9.960	59.624	109.288	7.388	21.151
1989				17.217	66.055	114.893	10.265	22.780
1990				30.995	57.188	83.382	20.362	16.134

ESTIMATES OF THOUSANDS OF METRIC TONS OF CRABS

POPULATION ESTIMATES
(point estimates and approx. 95% confidence intervals)

	RECRUITS			LEGALS			COMMERCIAL	NATURAL
YEAR	LOWER	POINT	UPPER	LOWER	POINT	UPPER	CATCH	DEATHS
1975				.000	80.779	279.542	23.281	24.503
1976				.000	110.163	444.247	28.994	34.280
1977				.000	117.878	481.262	31.737	36.457
1978				.000	136.578	642.985	39.743	41.311
1979				.000	136.658	559.439	48.910	38.476
1980				.000	99.591	324.035	58.944	20.754
1981				14.142	27.373	40.604	15.237	6.006
1982				5.558	9.332	13.106	1.361	3.246
1983				3.296	5.128	6.959	.000	2.018
1984				4.559	6.703	8.847	1.897	2.044
1985				4.528	7.383	10.238	1.894	2.313
1986				4.658	20.104	35.549	5.168	6.294
1987				8.213	21.803	35.393	5.574	6.835
1988				4.518	27.045	49.573	3.351	9.594
1989				7.810	29.962	52.115	4.656	10.333
1990				14.059	25.940	37.822	9.236	7.318

Table 6. Continued.

PARAMETER SUMMARY

NUMBER OF YEARS = 16

NUMBER OF AGE CLASSES = 2

NUMBER OF RESIDUAL ERRORS = 46, AS FOLLOWS:

15 FOR RECRUIT MEASUREMENT ERRORS (ALL YEARS BUT LAST),
16 FOR POST-RECRUIT MEASUREMENT ERRORS (ONE EACH YEAR),
15 FOR EQUATION ERRORS (ONE FOR EACH EQUATION)

NUMBER OF PARAMETERS TO BE ESTIMATED = 32, AS FOLLOWS:

ONE FOR TRUE POST-RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR,
ONE FOR TRUE RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR
(EXCEPT THE LAST YEAR), AND ONE FOR Q.

DEGREES OF FREEDOM = 14 (NO. OF RESIDUALS MINUS NO. OF PARAMETERS)

PARAMETERS ESTIMATED INDEPENDENT OF MODEL

RECRUIT CATCHABILITY = 1.00 TIMES ADULT CATCHABILITY

COMMERCIAL CATCH OCCURS 3.0 MONTHS AFTER SURVEY

INSTANTANEOUS NATURAL MORTALITY = .5

RELATIVE ERROR WEIGHTS

EQUATION ERROR	1.00
RECRUIT OBSERVATION ERROR	1.00
LEGAL OBSERVATION ERROR	1.00

NON-LINEAR LEAST-SQUARES FIT

NUMBER OF ITERATIONS = 8

NUMBER OF FUNCTION EVALUATIONS = 9

SUM OF SQUARES = 2.14

CATCHABILITY COEFFICIENT (X10**-6)

INITIAL GUESS	1.00000	
FINAL ESTIMATE	.89969	
95% CONFIDENCE INTERVAL (	.56011,	1.23927)
ESTIMATED STANDARD ERROR	.15831	

Table 7. Estimates of abundance from the measurement error model with $M=0.5$.

ESTIMATED RELATIVE ABUNDANCE

	RECRUITS				POST-RECRUITS			
YEAR	OBSERVED	ESTIMATED	RESIDUAL	EST SE	OBSERVED	ESTIMATED	RESIDUAL	EST SE
1975	12.800	18.681	-5.881	.029	8.200	10.050	-1.850	.536
1976	18.300	25.712	-7.412	.244	14.400	11.438	2.962	NA
1977	19.200	24.939	-5.739	.380	18.400	15.448	2.952	NA
1978	26.400	31.377	-4.977	.396	20.200	16.610	3.590	NA
1979	22.700	24.748	-2.048	.458	21.200	19.059	2.141	NA
1980	18.600	17.730	.870	.519	17.500	15.366	2.134	NA
1981	2.600	2.264	.336	.638	8.700	6.136	2.564	NA
1982	2.200	1.294	.906	1.040	2.500	1.549	.951	NA
1983	.700	.591	.109	.849	.800	1.368	-.568	NA
1984	2.100	1.354	.746	.700	1.000	1.188	-.188	NA
1985	1.900	1.827	.073	1.725	.600	1.007	-.407	NA
1986	4.800	6.438	-1.638	1.343	1.100	1.214	-.114	NA
1987	4.000	4.320	-.320	.560	3.900	3.238	.662	NA
1988	3.700	5.971	-2.271	.530	2.700	3.175	-.475	NA
1989	4.300	5.052	-.752	.509	7.600	4.729	2.871	NA
1990	3.000	NA	NA	NA	6.200	4.813	1.387	NA

P O P U L A T I O N   E S T I M A T E S

NUMBERS OF CRABS IN MILLIONS

YEAR	RECRUITS	POST-RECRUITS	LEGALS	COMMERCIAL CATCH	NATURAL DEATHS	LEGAL POUNDS	BIOMASS TONS
1975	19.306	10.387	29.693	9.005	8.868	169.253	76.773
1976	26.574	11.821	38.395	10.653	11.776	230.368	104.494
1977	25.774	15.966	41.740	11.859	12.715	246.267	111.706
1978	32.428	17.166	49.594	15.107	14.790	287.647	130.476
1979	25.577	19.698	45.274	16.848	12.546	289.757	131.433
1980	18.324	15.881	34.205	20.959	6.905	212.072	96.195
1981	2.339	6.342	8.681	5.332	1.748	54.690	24.807
1982	1.337	1.601	2.938	.536	.988	16.452	7.462
1983	.611	1.413	2.025	.000	.797	10.933	4.959
1984	1.399	1.228	2.627	.804	.782	13.661	6.197
1985	1.888	1.041	2.929	.759	.915	16.108	7.307
1986	6.654	1.255	7.909	2.110	2.452	42.707	19.372
1987	4.464	3.347	7.811	2.119	2.411	45.305	20.550
1988	6.171	3.281	9.453	1.231	3.334	56.716	25.726
1989	5.222	4.887	10.109	1.683	3.451	61.664	27.971
1990	3.101	4.975	8.075	3.133	2.198	52.488	23.809

Table 7. Continued.

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        PARAMETER SUMMARY

NUMBER OF YEARS = 16

NUMBER OF AGE CLASSES =  2

NUMBER OF RESIDUAL ERRORS = 31, AS FOLLOWS:

        15 FOR RECRUIT MEASUREMENT ERRORS (ALL YEARS BUT LAST),
        16 FOR POST-RECRUIT MEASUREMENT ERRORS (ONE EACH YEAR),

NUMBER OF PARAMETERS TO BE ESTIMATED = 17, AS FOLLOWS:

        ONE FOR TRUE POST-RECRUIT RELATIVE ABUNDANCE IN FIRST YEAR,
        ONE FOR TRUE RECRUIT RELATIVE ABUNDANCE FOR EACH YEAR
        (EXCEPT THE LAST YEAR), AND ONE FOR Q.

DEGREES OF FREEDOM = 14 (NO. OF RESIDUALS MINUS NO. OF PARAMETERS)

         PARAMETERS ESTIMATED INDEPENDENT OF MODEL

RECRUIT CATCHABILITY =  1.00 TIMES ADULT CATCHABILITY

COMMERCIAL CATCH OCCURS   3.0 MONTHS AFTER SURVEY

INSTANTANEOUS NATURAL MORTALITY =  .5


                  RELATIVE ERROR WEIGHTS

RECRUIT OBSERVATION ERROR        1.00
POST-RECRUIT OBSERVATION ERROR   1.00


          NON-LINEAR LEAST-SQUARES FIT

NUMBER OF ITERATIONS =              7

NUMBER OF FUNCTION EVALUATIONS = 135

SUM OF SQUARES = 2.723


              CATCHABILITY COEFFICIENT (X10**-6)

INITIAL GUESS                1.00000
FINAL ESTIMATE                .96758
95% CONFIDENCE INTERVAL (  -.17304,  2.10821)
ESTIMATED STANDARD ERROR      .53176
```

versions model examined so far, it appears that abundance of legal male crabs may have been underestimated in 1988 and overestimated in 1989 by the trawl survey. While this was suspected by many fishery biologists at the time given a two-fold increase in estimated abundance of legal male crabs without significant recruitment (Table 1), a formalized model framework was not available then to evaluate objectively the evidence for this conjecture.

Draft Work Plan

Although we are encouraged by these preliminary results of this population estimation model as a potential applied management tool, we feel that further model development and testing in several areas is necessary prior to full implementation. First, estimation of instantaneous natural mortality and its effects on population size estimation deserve further research. The time-structure of measurement and process errors may be indicative of annual changes in instantaneous natural mortality. To investigate this, we plan to develop a new version of the estimation model that incorporates $M(t)$ using estimates of mortality derived independent of the model. Second, we would like to investigate the magnitude of shell ageing errors and their implications to population estimation. Differences exist in proportions of recruits and post-recruits between survey catches (Table 1) and catch samples (Table 2). The reasons for discrepancies are not obvious. Third, given recent changes in management strategies for king crabs, it may be desirable to develop a new model that estimates abundance of *mature* male crabs rather than *legal* male crabs. Fourth, we plan to select a "standard" version of the model for further development and testing. To do so, we need to evaluate the merits of the mixed error and all observation error versions of the model. Last, we plan to develop bootstrap methods to calculate variances of population abundance estimates. Any comments on the model, preliminary results, and future work plan are welcomed by the authors.

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