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DETERMINATION OF MINIMUM SIZE AND YIELD LIMITATIONS FOR TANNER CRABS IN THE EASTERN BERING SEA

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and
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NOTICE

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INTRODUCTION

Two closely related crab species in the genus *Chionoecetes*, (*C. bairdi* and *C. opilio*) and a hybrid of the two, all commonly referred to as snow (Tanner) crab, are presently being harvested in the eastern Bering Sea. Prior to 1964 Tanner crabs were harvested incidentally in the King crab fisheries. In 1964, the United States (U.S.) ratified the 1958 Continental Shelf Convention and declared King and Tanner crabs (among other species) as "creatures of the continental shelf," and consequently obtained exclusive rights to manage the resources. Bilateral agreements negotiated in that same year with both Japan and the Union of Soviet Socialist Republics (U.S.S.R.) (while the King crab fisheries of both countries were at their peak) resulted in immediate reductions in the foreign catch quotas of King crabs. Consequently, the foreign fisheries shifted their emphasis to Tanner crabs. In 1969, agreements were also negotiated to reduce the foreign Tanner crab catches. The U.S.S.R. discontinued its King and Tanner crab fisheries after 1971 but Japan has continued its at reduced levels.

Up until 1974, the United States King crab fishery harvested Tanner crabs only incidentally. Since then, however, a purposeful Tanner crab fishery has developed, and catches of Tanner crab have grown from 2.5 million crabs in 1974 to more than 8.9 million crabs in 1976 (Department of Commerce 1977). This rapid rate of growth has resulted in a need for regulation to promote orderly development of the fishery. A preliminary management plan for the 1977 eastern Bering Sea Tanner crab fishery was implemented under the mandate of the Fishery Conservation and Management Act of 1976 (U.S. Public Law 94-265).

The plan (Department of Commerce 1976) in effect calls for (1) a total catch quota of 37,400 metric tons (30,000 mt for C. bairdi and 7,400 mt for C. opilio), (2) a foreign catch quota of 12,500 mt of both species combined--which is the surplus over the domestic need for 24,900 mt. A size limit of 140 mm carapace width for C. bairdi is also in effect for the domestic fishery as are gear-area-time restrictions on both the domestic and foreign fisheries.

As the Tanner crab fishery management plan is refined, it must be based on a synthesis of information concerning both the biology of the species and the socio-economic factors governing the fishery. In this paper we discuss from a biological perspective the two most important aspects of establishing a minimum size limit for crabs taken in the fishery--(1) maximizing yield and (2) maintaining a high reproductive potential in the population. No specific size limit is recommended; rather the intent is to provide an analytical basis for evaluating the consequences to stock productivity which are expected to result from various minimum size regulations. Data are specifically provided to allow one to examine such consequences as they affect yield and reproductive potential in light of current knowledge of population size, age group composition, yield-per-recruit theory, sex ratio, and maturity schedule. Year class strengths for Tanner crabs are also computed in order to predict their recruitment patterns into the fishery through 1980.

GENERAL DISTRIBUTION AND DENSITY PROFILE

Data used in describing the general distribution and in subsequent sections were collected on National Marine Fisheries Service (NMFS) crab survey cruises in the eastern Bering Sea during 1969-1976. The sampling area has varied somewhat between cruises, but a region bounded on the south by the Alaskan Peninsula, on the west by a line drawn from Unimak Island to the Pribilof Islands, and on the north by a line drawn from the Pribilof Islands to Port Moller, has been consistently sampled each year. This region includes most of the _C. bairdi_ stock, but only the extreme southern part of the _C. opilio_ stock. In 1975 an OCSEAP* baseline survey was conducted over a more extensive part of the Bering Sea. Data from this cruise provide a better assessment of the distribution and abundance of Tanner crabs on the eastern Bering Sea than was previously available.

The general distribution of the two Tanner crab species and their hybrid is influenced largely by water temperature. _Chionoecetes opilio_ occurs in cold water, from the Chukchi Sea southward to Bristol Bay. _Chionoecetes bairdi_ occurs in relatively warm water from Puget Sound northward to the eastern Bering Sea. The taxonomic affinity of these two species is demonstrated by the large number of hybrids found in regions where their ranges overlap.

Chionoecetes bairdi

According to the August-October 1975 OCSEAP base-line survey, _C. bairdi_ were distributed widely in the eastern Bering Sea (Figure 1). The scope of

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* In 1974, the National Oceanic and Atmospheric Administration (NOAA) contracted with the Bureau of Land Management of the Department of Interior to provide an environmental assessment of the northeastern Gulf of Alaska and the eastern Bering Sea. This established the Outer Continental Shelf Environmental Assessment Program (OCSEAP).

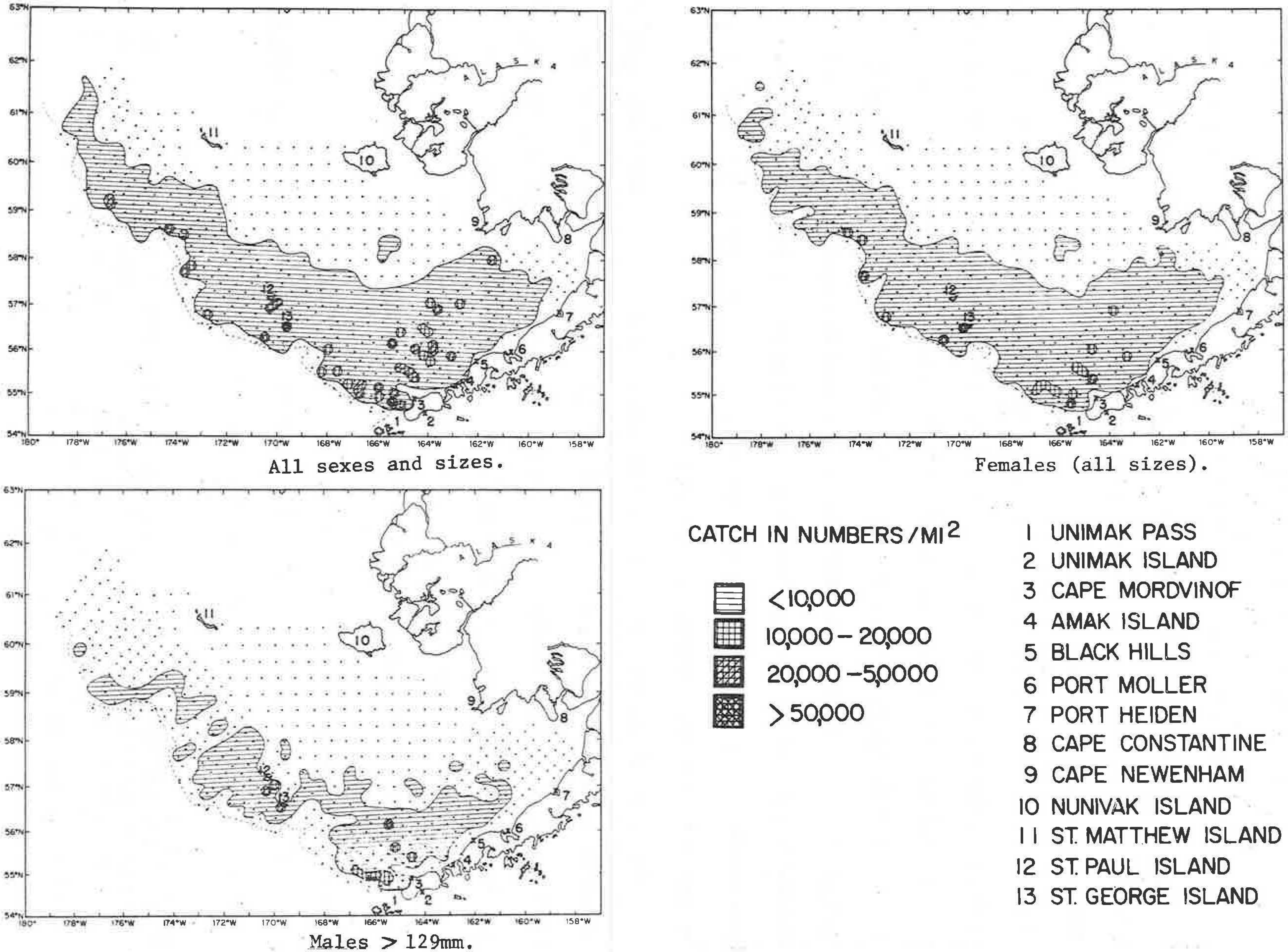


Figure 1. Distribution of Chionoecetes bairdi in the 1975 OCSEAP survey area. (Figure from NWAFC 1976)

the survey, which is the largest conducted by NMFS, was still not extensive enough to delineate the entire distribution pattern of the population. The pattern along the western boundary of the survey area indicates that the population may extend farther westward than the area sampled, although the abundance there is apparently low. The major concentrations of *C. bairdi* were distributed between the Pribilof Islands and the Alaskan Peninsula. Concentrations of *C. bairdi* females were scattered in an arc along the northern coast of Unimak Island, and northwest of the Pribilof Islands along the edge of the Continental Shelf. The largest concentration was found just south of St. George Island. Large males (greater than 129 mm in carapace width) did not extend as far north as smaller sized males nor farther east than Port Moller in the Bristol Bay region. The major concentrations of mature males appear to occur north of Unimak Island and near the Pribilof Islands.

The density profile of *C. bairdi* population in the eastern Bering Sea, as depicted by catch rates in the OCSEAP survey, is shown in Figure 2. Major concentrations are found to the north of Unimak Island (Subareas 1 and 2) and around the Pribilof Islands (Subareas 2 and 3).

The occurence of *C. bairdi* was high throughout the 1975 OCSEAP survey area. The species was caught in at least 50% of the hauls in the following areas: subarea 1 (96%), subarea 2 (85%), subarea 3 (70%) and subarea 4 (50%).

The population, as a percentage of total numbers, was found to be distributed as follows: subarea 1 (24%), subarea 2 (47%), subarea 3 (26%) and subarea 4 (less than 1%).

Chionoecetes opilio

The distribution of *C. opilio* is very similar to that for *C. bairdi*, except that the longitudinal range of *C. opilio* is wider--especially north of 58°N (Figure 3). The limits of its range probably extend even farther west and north of the area covered by the 1975 OCSEAP survey.

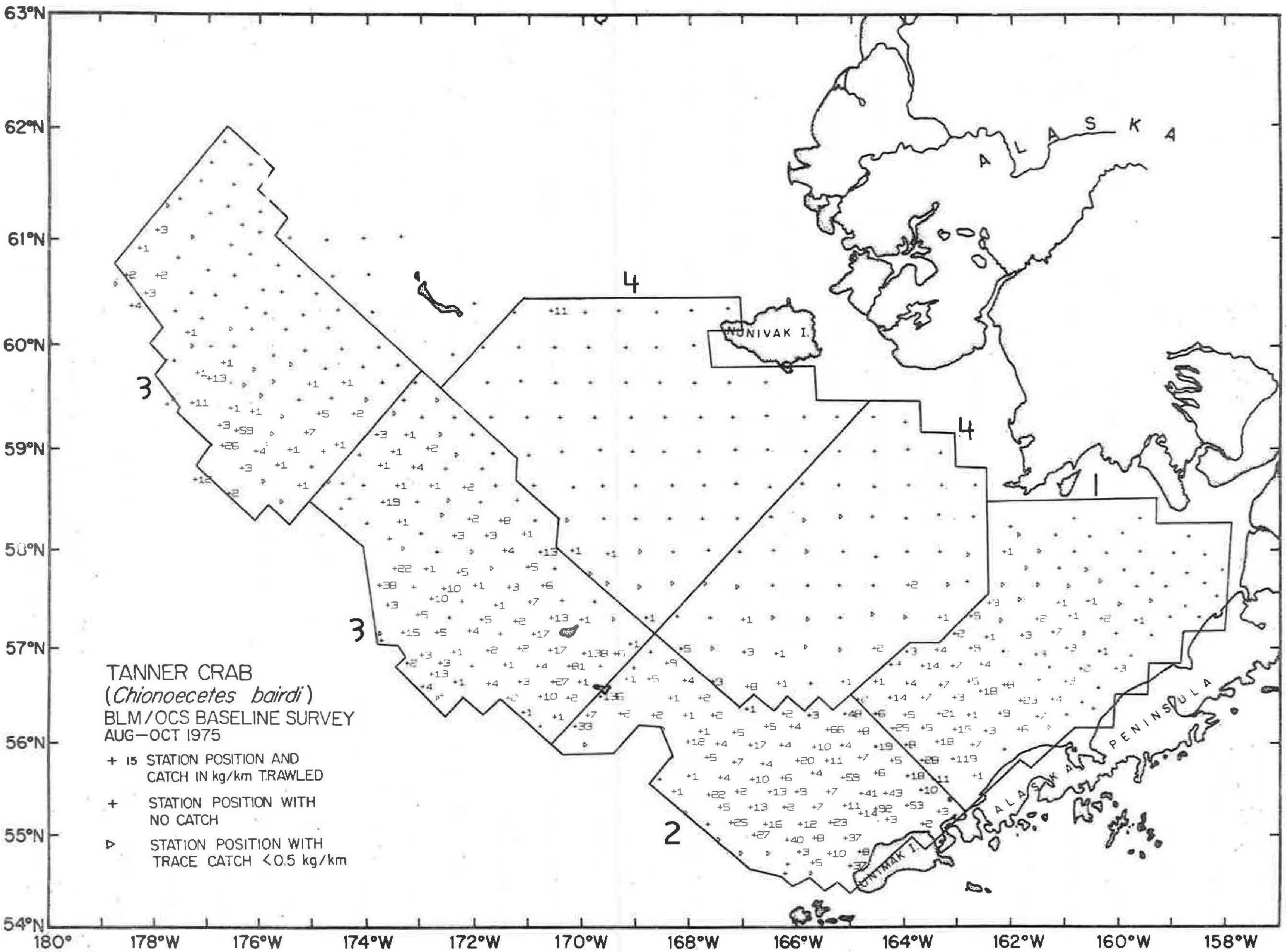


Figure 2. Density profile of Chionoecetes bairdi population in the 1975 OCSEAP survey area. (Figure from NWAFC 1976)

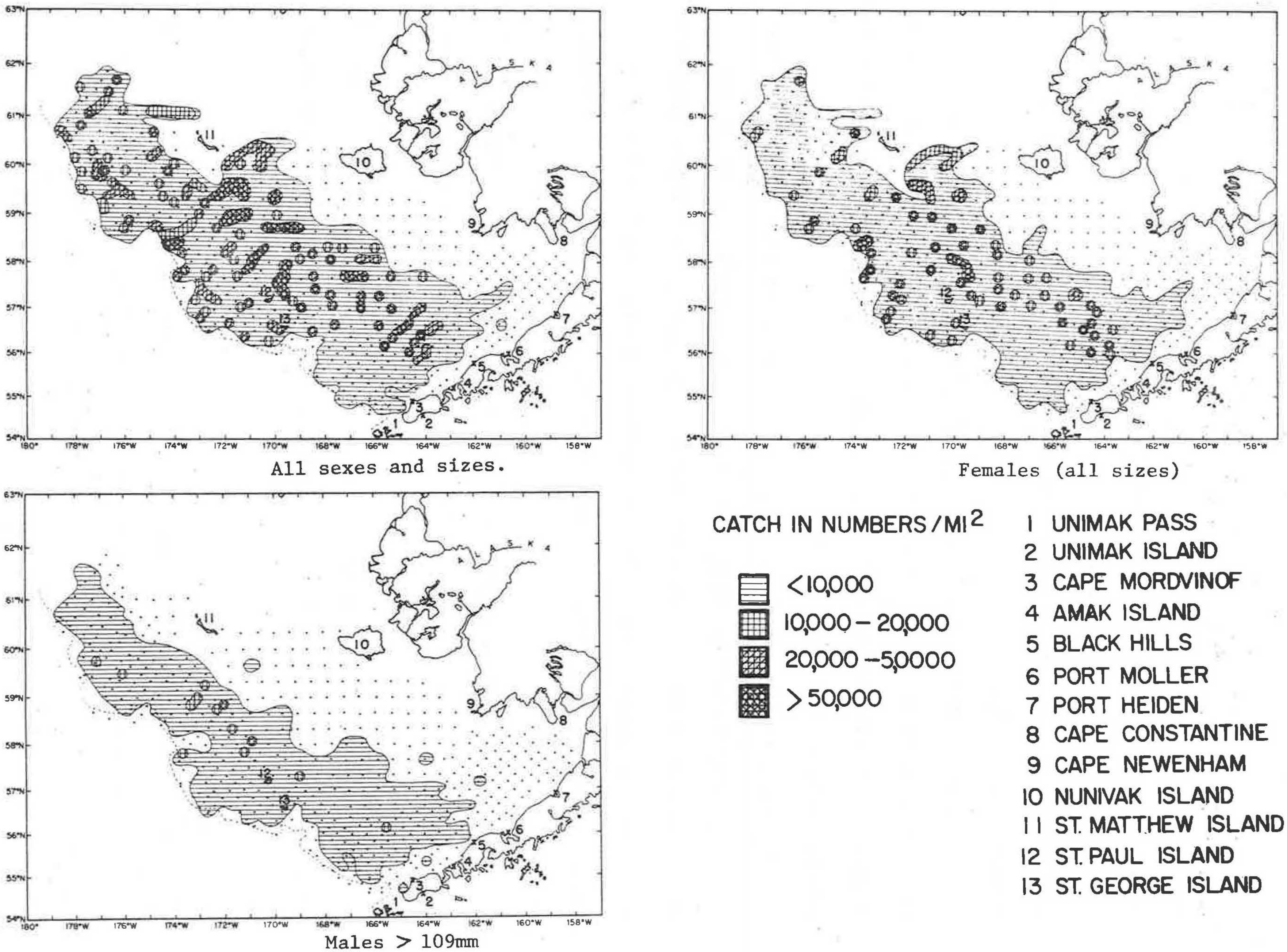


Figure 3. Distribution of Chionoecetes opilio in the 1975 OCSEAP survey area. (Figure from NWAFC 1976)

In contrast to *C. bairdi*, large concentrations of *C. opilio* females were quite predominant north of the Pribilof Islands and in a wide band extending from the Pribilof Islands southeastward toward Amak Island (Figure 3). Concentrations of females were noticeably missing south of a line between Amak and St. Paul Island, a pattern in contrast to that of the distribution of female *C. bairdi*.

As in the case for large male *C. bairdi*, large male *C. opilio* (greater than 109 mm in carapace width) were found in a narrow band within their range (Figure 3). Concentrations of large *C. opilio* were scattered in a band running northwesterly from the Pribilof Islands.

A density profile of the *C. opilio* distribution is quite different from that of *C. bairdi*, with *C. opilio* densities being highest in areas to the north and west of the main concentrations of *C. bairdi*. The largest proportion of catches of *C. opilio* was obtained northwest of St. Paul Island (Figure 4). In comparison, the largest proportion of *C. bairdi* was found just north of Unimak Island.

The occurence of *C. opilio* was high throughout the 1975 OCSEAP survey area and *C. opilio* were caught in 79% to 90% of all hauls, depending on the subarea.

The population, as a percentage of total numbers, was found to be distributed as follows: subarea 1 (9%), subarea 2 (2%), subarea 3 (31%) and subarea 4 (58%).

Chionoecetes hybrid

Hybrid Tanner crabs (*C. opilio* x *C. bairdi*) were generally found throughout the 1975 OCSEAP baseline survey area but in smaller numbers than either *C. bairdi* or *C. opilio*. The relative abundance of the hybrid population was about 8% of all tanner crab numbers in the survey area as compared to 14% for *C. bairdi* and 78% for *C. opilio* (NWAFC 1976).

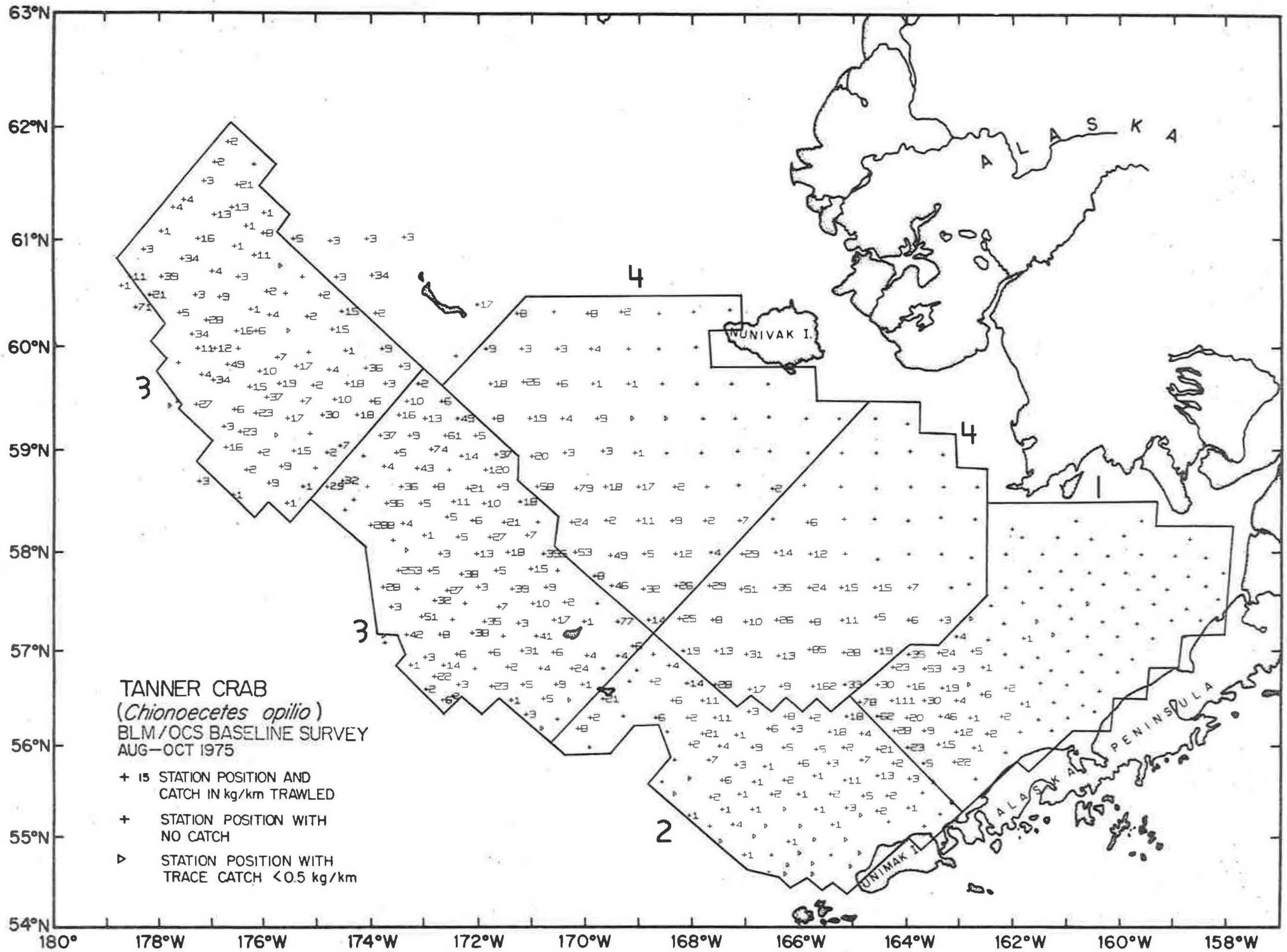


Figure 4. Density profile of Chionoecetes opilio population in the 1975 OCSEAP survey area. (Figure from NWAFC 1976)

The hybrid population occurred in the north and along the outer continental shelf and diminished in abundance in the southeastern part of the Bering Sea. It was found to be distributed as follows: subarea 1 (3%), subarea 2 (8%), subarea 3 (20%) and subarea 4 (69%).

LOCATION OF THE FISHERY

As mentioned, United States and Japan are the only two nations currently fishing for Tanner crabs in the Eastern Bering Sea. Both fisheries operate in areas where mature male crabs are large and abundant. Therefore they are concentrated around the Pribilof Islands and north of Unimak Island (Figure 5) where male C. bairdi are concentrated. A large area within the range of large male C. bairdi is avoided apparently due to low abundance.

Since the fisheries select for large-size crabs, they also avoid the more northerly areas where the smaller C. opilio are prevalant (Figure 6). As a result of this size selection, the C. opilio resource is apparently underutilized.

Although both species are exploited purposefully in a rather small area in relation to the distribution of the resources, they are routinely caught as incidental species in the massive Soviet and Japanese trawl fisheries for groundfish. These incidental catches, although they are by regulation required to be "returned to the ecosystem", result in an annual calculated loss of 11,000 to 14,000 mt of harvestable-size males (Department of Commerce 1977).

Aside from specific time-area regulations, it is apparent that the location of present fisheries for Tanner crabs is largely influenced by minimum size requirements and abundance of large males. Therefore, if either the minimum size requirement or the abundance of large males changes, it follows that the geographical pattern of the fisheries will also change and thereby result in a shift in burden of exploitation from one sector of the population to another. In this regard, the management plan must take into consideration area-time segregation in order to minimize fishing conflicts between the Japanese and the U.S. fisheries. However, the management plan must first examine the biological consequences of any changes in the minimum size limit.

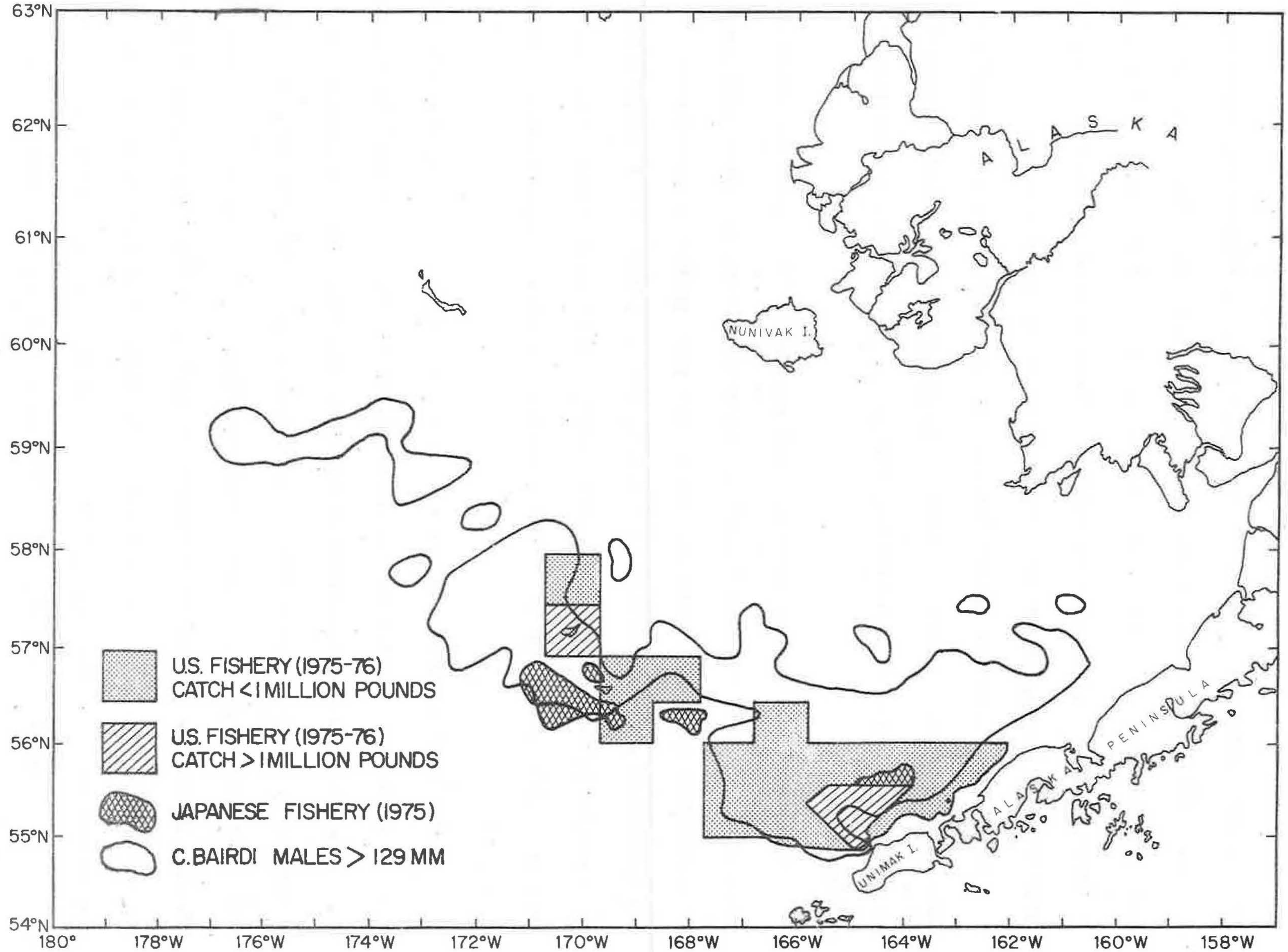


Figure 5. Location of U.S. and Japanese fisheries for Tanner crabs in relation to the distribution of large *Chionoecetes bairdi* males

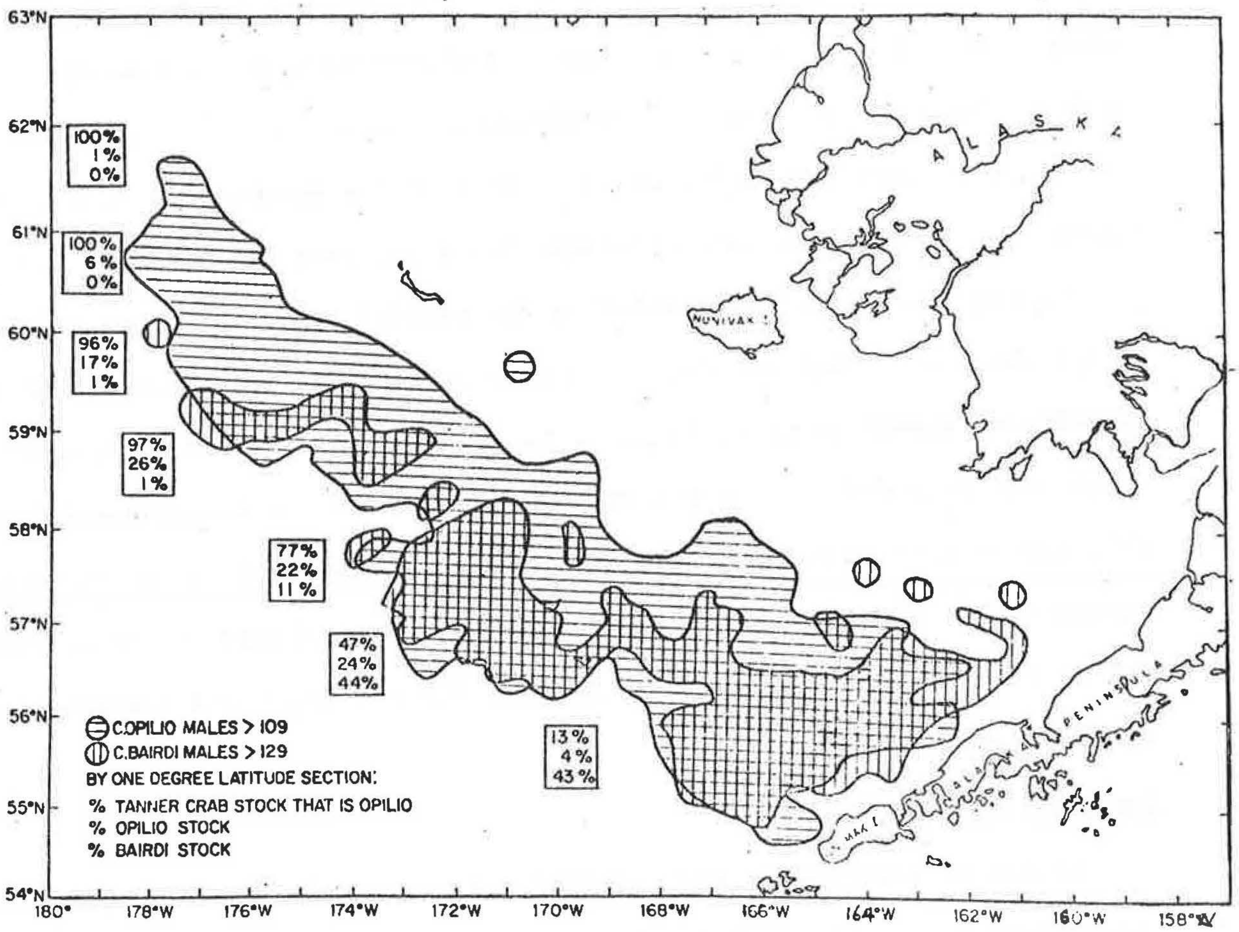


Figure 6. Distribution of Tanner crab stocks and species composition of large male Tanner crabs.

EFFECTS OF A MINIMUM SIZE LIMIT ON EQUILIBRIUM YIELD

The relationship between a minimum size limit and equilibrium yield can be assessed using yield per recruit (Y/R) theory. A yield model is used to determine the yield that can be obtained from a year class over its life-span when the innate growth characteristics of the species are modified by natural and fishery induced mortality. Yield per recruit is simply the yield produced by the year class divided by the initial number of recruits. Parameters which are necessary for yield calculations include constants of the generalized growth function (L_∞, k, t_0, δ); constants of the allometric weight-carapace width relationship (α, β); instantaneous natural mortality (M), age of recruitment (t_ρ), and maximum age of exploitation (t_λ). Given estimates for these parameters, yield per recruit surfaces can be calculated as a function of age at entry into the fishery ($t_{\rho'}$) and instantaneous fishing mortality (F).

Parameters of the Model

Growth of each Tanner crab species was estimated using a computer simulation model which incorporated both the expected growth increment per molt and the annual probability of molting. A generalized growth function, similar to the Chapman-Richards growth function, was fitted to simulated estimates of mean carapace width at each age. The resulting growth curves are shown in Figure 7 for both species. Estimated parameters of the generalized growth function are as follows:

	L_∞ (mm)	k	t_0 (years)	δ
C. bairdi	201	0.194	-4.8	7.5
C. opilio	161	0.168	-11.4	19.0

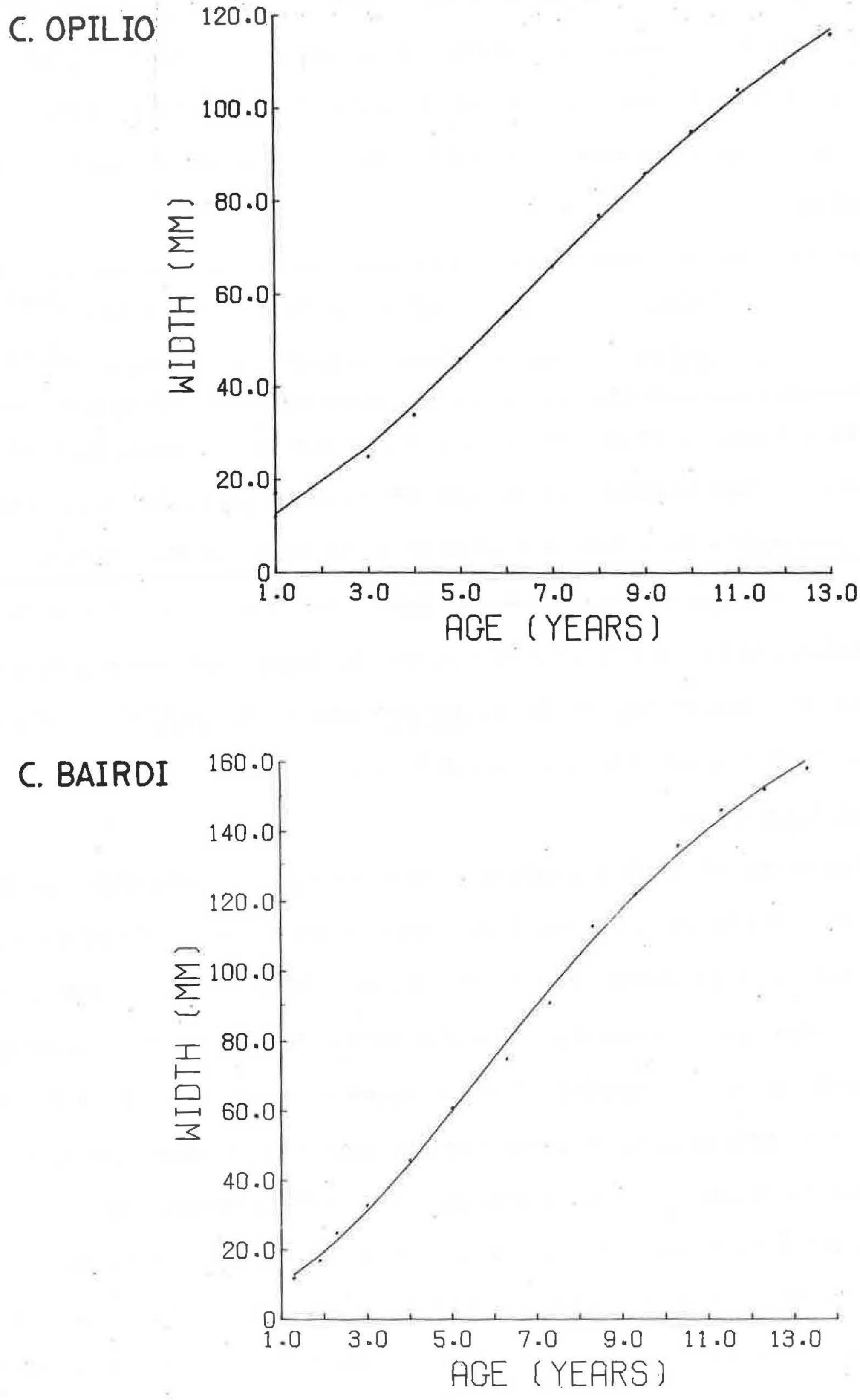


Figure 7. Relationship of carapace width to age for Chionoecetes opilio and Chionoecetes bairdi.

Maximum age is approximately 14 years for both species, and all males above a specified age at entry are assumed to be subject to capture, thus t_{λ} equals 14. Age of recruitment (t_{ρ}) was arbitrarily chosen to be 4 years.

The weight-carapace width relationship estimated for each species is as follows:

C. bairdi	weight (gm) = 0.00019 (width (mm))$^{3.0989}$
C. opilio	weight (gm) = 0.00023 (width (mm))$^{3.1295}$

No reliable estimate of natural mortality is presently available. but considering that maximum age is approximately 14 years for both species, it is reasonable to assume M lies within the range of 0.1 to 0.3.

Using the parameters estimated above, surfaces of yield per recruit were calculated as a function of $t_{\rho'}$, and F. These surfaces are displayed as contour plots in Figures 8 (C. bairdi) and 9 (C. opilio) for the particular cases of M equal to 0.1, 0.2, and 0.3.

Fishing Strategies

Two types of optimal fishing strategies can be represented by lines drawn on a yield surface. One line connects the locus of F values which maximize yield at each level of $t_{\rho'}$. The second (dashed) line, known as the eumetric fishing curve, connects the locus of $t_{\rho'}$ values which maximize Y/R at each level of F. The eumetric fishing curve is considered the more efficient of the two optimal fishing strategies because it minimizes the fishing effort required to obtain the same given amount of Y/R. However, for any particular age of entry, a larger Y/R can be achieved if F is allowed to be greater than that defined on the eumetric fishing line. The eumetric fishing curves drawn on the yield surfaces in Figures 8 and 9 are seen to be aysmptotic

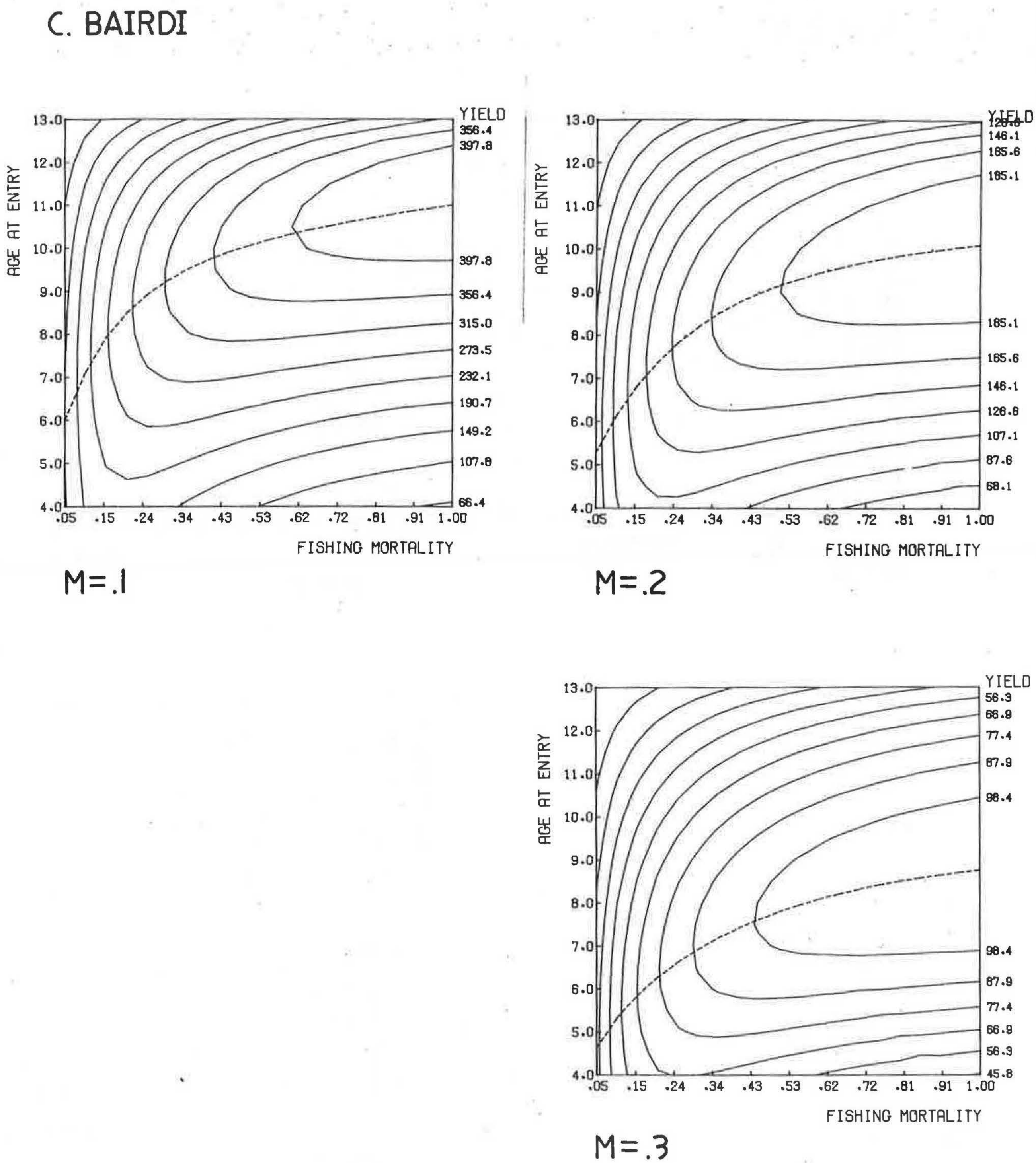


Figure 8. Yield isopleths for Chionoecetes bairdi at three rates of natural mortality based on the yield-per-recruit theory.

C. OPILIO

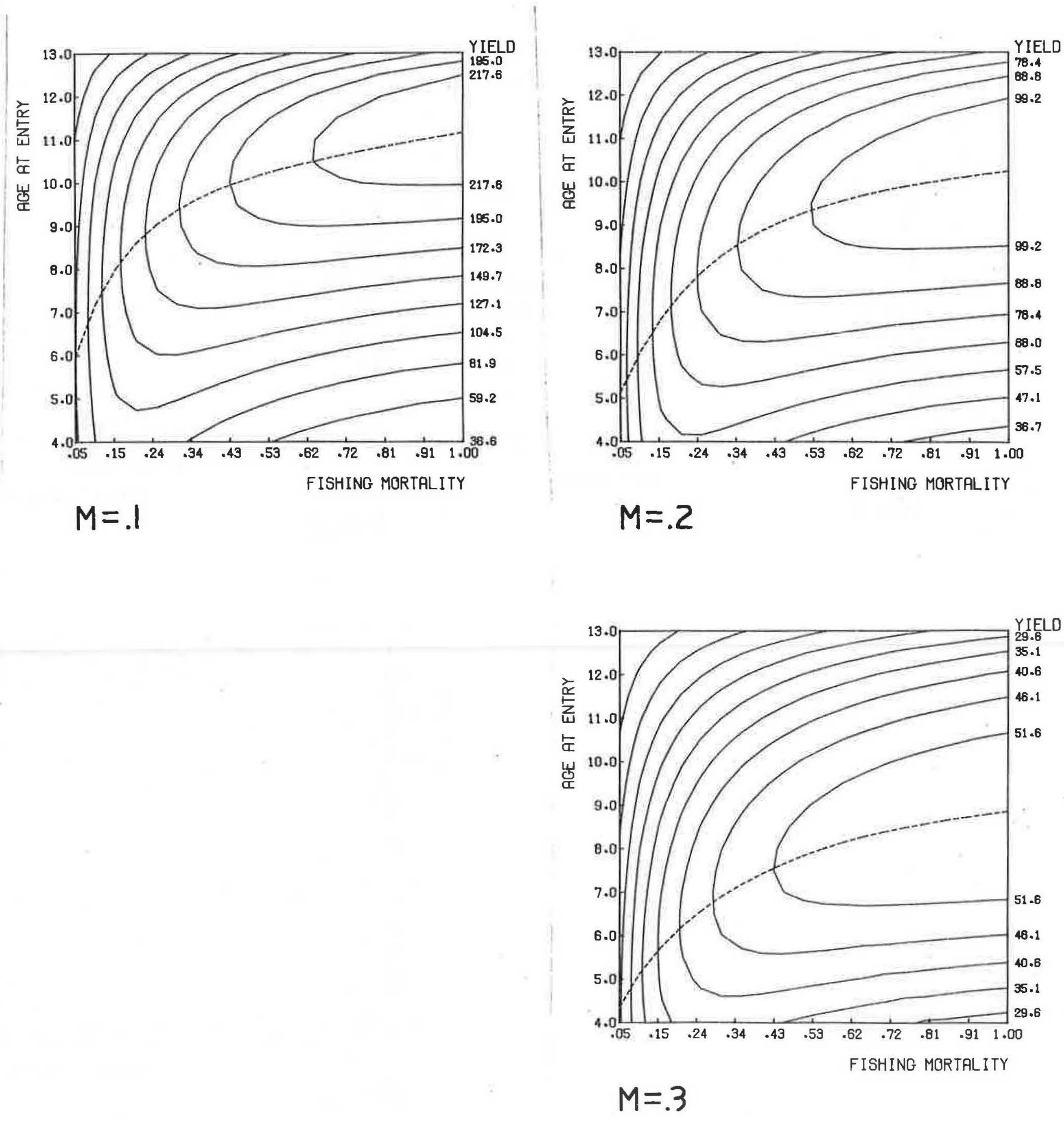


Figure 9. Yield isopleths for Chionoecetes opilio at three rates of natural mortality based on the yield-per-recruit theory.

functions of F, thus maximum Y/R is reached as F approaches infinity. This yield could only be achieved if a cohort were instantaneously harvested at an age (the critical age, t_c) when its biomass is maximum. Since instantaneous harvesting is normally not possible, a compromise between yield and F (and $t_{\rho'}$, if fishing is not eumetric) must be made. Ultimately this compromise will be determined by economic factors, especially the incremental return to a fishery due to increasing F.

In the absence of economic information, an optimum level of F cannot be explicitly defined. A reasonable estimate of minimum size which maximizes Y/R can still be made, though, even if F is not well known. This is because eumetric $t_{\rho'}$ is relatively insensitive to changes in F above some moderate level of fishing mortality. For example, if F is assumed to eventually stabilize in the neighborhood of 0.5, an optimum age and size at entry at three levels of natural mortality can be calculated. These are shown in the following table. Included are the critical ages, t_c, when F approaches infinity.

		F = 0.5		F approaching infinity
	M	$t_{\rho'}$ (years)	width (mm)	t_c (years)
C. bairdi	.1	10.1	128	15.0
	.2	9.2	121	11.5
	.3	7.8	102	9.5
C. opilio	.1	10.2	97	16.1
	.2	9.3	87	12.0
	.3	7.8	75	9.6

Recruitment, Yield and Biomass

To convert Y/R to equilibrium annual yield from a population, one usually assumes that recruitment is constant. Under this assumption, at equilibrium, the yield from a year class over its lifespan is equivalent to the yield from the whole population in any one year. If the average number of recruits of age t_ρ, can be estimated, then equilibrium yield can be estimated from Y/R theory.

Recruitment strength was estimated for C. bairdi but not for C. opilio because of inadequate survey coverage of the latter species. The number of 4-year old male C. bairdi which could be reliably estimated was taken to represent recruitment (and year class) strength. To estimate the number of these crabs, a growth simulation model was used to estimate a size frequency distribution of successive age classes. This in turn was used in conjunction with the population size frequency estimates from the 1974-76 Bering Sea survey cruises to estimate the number of 5, 6 and 7-year old males in each year. No attempt was made to directly estimate 4 year old crabs because they appeared to be under-represented in the samples due to gear selectivity; however, they were indirectly estimated for previous years by correcting for a mortality each year class experienced since it was 4 years old. For instance, the number of 5 year old crabs in 1974 divided by its expected survival in one year ($e^{-0.2}$) was used as an estimate of the number of 4 year olds in 1973. In this manner the number of 4 year old males in the population was estimated for the years 1971-1975. These are shown below.

Year at age 4	Millions of 4-year old male C. bairdi during survey year: 1976	1975	1974	Mean
1971			161.6	161.6
1972		130.1	136.6	133.4
1973	83.7	93.7	99.4	92.3
1974	58.0	45.5		51.8
1975	28.3			28.3

Mean age 4 recruitment over 5 years = 93,500,000

For *C. bairdi*, the average recruitment of 4 year old males for 1971-75 was therefore estimated to be 93.5 million. Equilibrium yield was estimated by multiplying the estimated recruitment with eumetric Y/R values calculated for M = 0.2 (Table 1).

The equilibrium biomass of the exploited population is the biomass of the population of males larger than the size at t_{ρ}'. It is calculated by:

$$\text{equilibrium biomass} = \frac{\text{equilibrium yield}}{\text{exploitation rate}}$$

where

$$\text{exploitation rate} = \frac{F}{F+M} \quad (1-e^{-(F+M)})$$

Table 1.--Estimation of yield and biomass based on equilibrium conditions.

t_ρ' (years)	width (mm)	F	equilibrium yield (MT)	equilibrium biomass of exploited population (MT)
6.8	87	.15	11,117	87,838
7.4	95	.20	12,744	77,311
7.8	102	.25	13,968	69,383
8.2	106	.30	14,923	63,211
8.5	111	.35	15,699	58,314
8.8	114	.40	16,325	54,273
9.0	118	.45	16,849	50,920
9.2	121	.50	17,288	48,070
9.3	123	.55	17,662	45,646
9.5	124	.60	17,980	43,534
9.6	125	.65	18,242	41,662
9.7	126	.70	18,475	40,028
9.8	127	.75	18,672	38,566
9.9	128	.80	18,831	37,238

EFFECTS OF MINIMUM SIZE LIMITATIONS ON REPRODUCTIVE POTENTIAL

At present, the Tanner crab fishery is restricted to the males of the species. Any females caught incidentally are returned to the sea. The possibility exists that the reproductive potential of the species could be reduced if too many males are removed from the population, thereby decreasing chances of females' finding mates. If all males contribute equally to the reproduction process, a certain sex ratio would need to be maintained. However, a Tanner crab's contribution to reproduction changes with age, and therefore the optimum age distribution must be ascertained.

Reproductive characteristics

Until a Tanner crab's first puberty molt, there is no segregation by sexes. Upon reaching puberty, however, male Tanner crabs tend to disperse, while female crabs tend to remain grouped together, apparently for the remainder of their lives. Newly matured males tend to mate with newly matured females--some males possibly mating with several females. Female Tanner crabs can store sperm, possibly for a number of years, and therefore need not find mates each breeding season, although it is believed that females do mate at least once again after their first mating. In later matings, the female's partner is probably older and larger than her first post-pubescent mate. It is important to note, however, that unlike in King and Dungeness crabs, there appears to be no competition among the older males for access to the newly maturing females. It is primarily the younger, just matured crabs who mate with those females.

One can then group the population of mature males into two age categories: 1) the newly matured males who fertilize the newly matured females, and 2) the previously matured older, larger males who mate periodically with older females. According to trawl surveys, these two groups are actually segregated.

Of the entire adult female population, roughly half are newly matured individuals (*C. bairdi*, mean = 0.51, range = 0.29 - 0.73; *C. opilio*, mean 0.52, range = 0.15 - 0.94), which mate with the newly matured males. The fact that older females need not mate each year suggests that previously matured males (which couple with the older females) mate less often than newly matured males. Furthermore, the present within-group sex ratios in the population for *C. bairdi* (newly matured ♀/♂ = 1.5; previously matured ♀/♂ = .40) support the view that there is a difference between mature male groups in the number of matings per male required to maintain complete female insemination.

It can be concluded that newly matured male Tanner crabs contribute greatly to the reproductive success of the population, and therefore must be given some protection from exploitation. The older male crabs play less of a role in the reproductive process, and consequently might need less protection.

Sexual Groups

Since the sexual maturity of males is important in determining the reproductive potential of the population, one will have to estimate the relative abundance of principal sexual groups in order to assess the degree of protection offered to each group under different minimum size limitations. A male Tanner crab at any size can be classified into the groups shown in Figure 10. The crab may be immature or mature. If mature, it belongs to one of three categories:

(1) Group 1 -- a crab which becomes mature at this size,

(2) Group 2 -- a crab which has matured at this size in previous years but has not grown, and

(3) Group 3 -- a crab which has matured at a smaller size in previous years and has grown to this size.

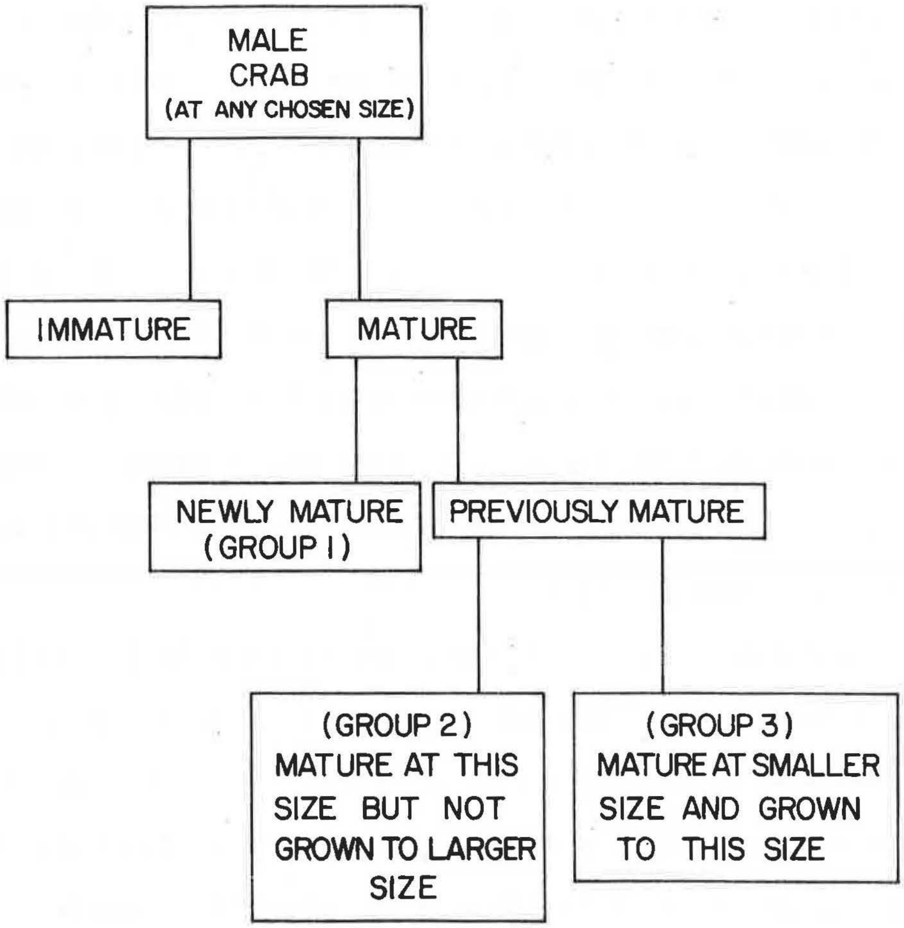
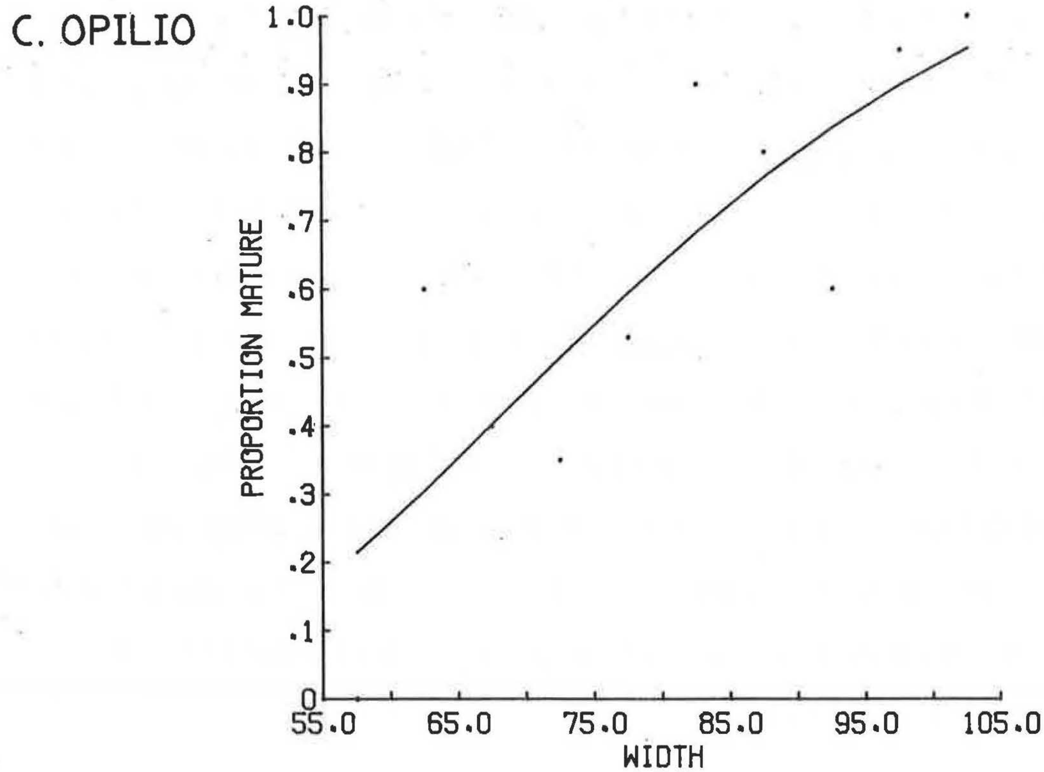


Figure 10. Principal groups of male Tanner crabs according to their sexual development important to reproductive potential.

In terms of reproductive roles, it is important to estimate the relative abundance of crabs classified as: (a) immature, (b) newly matured (group 1), and (c) previously matured (groups 2 and 3). To determine the numbers of immature and mature crabs, a computer simulation model was developed using information concerning the growth and maturity pattern for each species. A maturity schedule (Figure 11) was constructed from data on carapace width and chaela length, assuming that differential growth occurs at sexual maturity. This schedule, which represents the cumulative probability of being mature as a function of size, was used to estimate the number of immature and mature males by 1 mm size interval from size frequency histograms of Bering Sea survey data. As noted in Figure 10, no further division need to be made for the immature class.

For the mature class, it is necessary to separate the newly matured (group 1) from the previously matured (groups 2 and 3) crabs. This is done by incorporating several aspects of growth into the simulation model. A molting probability schedule was constructed from carapace age data collected in the Bering Sea. Using this schedule the expected fraction of males in any size group that will not molt was calculated and subtracted from the number of mature crabs. This procedure separated group 2 crabs from all mature crabs. Considering both the molting probability schedule and the expected growth increment per molt, the expected number of males that matured at one size and then grew to a larger size in the following year was estimated (group 3 crabs). These males (both groups 2 and 3) form the previously matured group and by subtraction from the mature group, the newly matured group (group 1) was estimated.

In order to assess how much protection is given to each group of males under different size limits, the output of the model was expressed as the



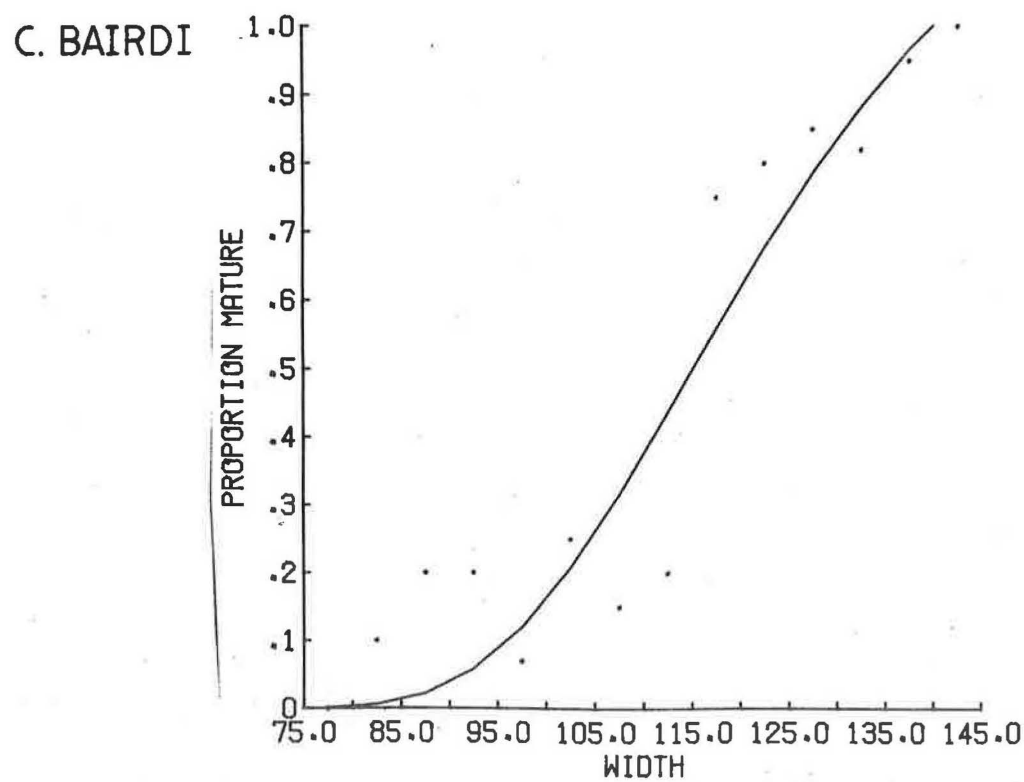


Figure 11. Maturity schedule for male Chionoecetes opilio and Chionoecetes bairdi at different sizes (carapace width in mm).

percent protection given to the immature group and the two mature groups for male crabs larger than some reference size (60 mm for C. bairdi and 40 mm for C. opilio) as a function of minimum size limits (Figure 12). The graphs show the 8-year average (1969-76) degree of protection given to the two species of Tanner crabs. For instance, under the present minimum size regulation for C. bairdi at 140 mm carapace width, it appears that (a) almost 100% of the immature group of crabs are protected from exploitation, (b) about 92% of the newly matured group are similarly protected, and (c) only about 35% of the previously matured group are protected.

In the next section, Estimation of Biomass, the actual abundance of crabs in each of these groups in 1976 is calculated to show the absolute degree of protection.

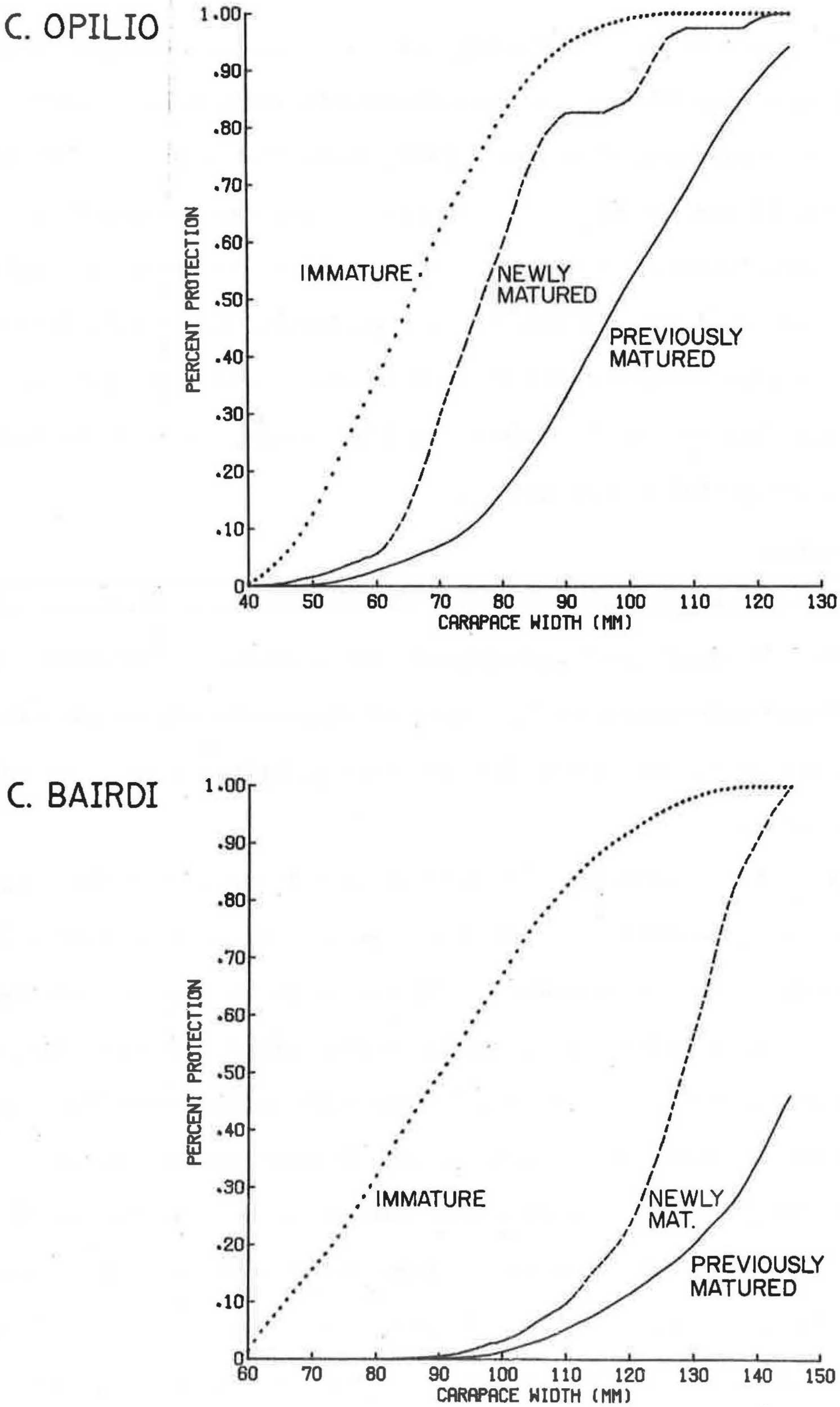


Figure 12. Degree of protection (1969-75 average) offered to the mature and immature groups of male Chionoecetes opilio and Chionoecetes bairdi larger than some reference size (40mm for C. opilio and 60mm for C. bairdi) as a function of minimum size limits.

ESTIMATION OF BIOMASS

The Tanner crab biomass for 1976 was high in comparison to that of previous years as reported in the 1977 Preliminary Fishery Management Plan for King and Tanner crabs (Department of Commerce 1977, Table 2). In this report additional details about the biomass of the two principal species are presented to allow one to examine consequences of minimum size limitations as they relate to defining allowable yields and protecting reproductive potential. Besides using information previously presented, such an examination must take into consideration the data on (1) the biomass by size groups, and (2) the biomass by stages of maturity within size groups.

Chionoecetes bairdi

In 1976, the *C. bairdi* population was estimated to be as follows: males (426 million, 223 thousand tons) and females (395 million, 70 thousand tons) (Appendix 1). These estimates possibly included almost the entire population since survey coverage has indicated that not many *C. bairdi* were found outside the survey area.

Table 3 provides information on the number and biomass of crabs larger than specified sizes, beginning at 100 mm and proceeding in 5 mm increments (for additional details, see Appendix 1). If one wants to impose a minimum size of 140 mm carapace width for *C. bairdi* in the fishery, one can see from Table 3 that there were apparently 124,000 tons (109 million crabs) of male *C. bairdi* in 1976 that met this criterion. Exactly how much can safely be taken from this 124,000 tons is a different matter and will be discussed in the next section. One will have to consider that the entire biomass may not be accessible to the fishery and that part of this biomass may need special protection. Since it has been previously noted that most of the eggs are fertilized by newly matured male crabs, it is highly desirable that this particular group be protected.

Table 2.—Annual abundance estimates (millions of crabs) for Tanner crabs from NOAA RV Oregon surveys in the eastern Bering Sea.

Sex	Size group*	1973	1974	1975	1976	95% confidence limits for 1976		
						Lower	Upper	%
C. bairdi								
Males	< 85	62.8	200.7	116.3	136.8	113.3	160.3	17
	85-129	140.5	255.0	207.5	131.7	120.2	143.2	9
	> 129	66.9	130.5	209.6	157.8	140.5	175.1	11
Total males		270.2	586.2	533.4	426.3	394.9	457.7	7
Females	< 85	47.9	210.5	120.8	174.7	143.3	206.1	18
	> 84	90.3	175.7	102.2	220.4	187.0	253.8	15
Total females		138.2	386.2	223.0	395.1	349.2	295.1	12
Total population		408.4	972.4	756.4	821.4	765.8	877.0	7
C. opilio								
Males	< 110	115.2	1,480.3	1,916.7	2,221.1	1,737.1	2,705.1	22
	> 109	84.7	246.7	274.8	181.6	110.4	252.8	39
Total males		199.9	1,727.0	2,191.5	2,402.7	1,913.5	2,891.9	20
Females	< 65	26.4	1,415.3	3,213.1	4,867.1	3,240.0	6,494.2	33
	> 64	26.8	195.9	194.3	697.3	536.5	858.1	23
Total females		53.2	1,611.4	3,407.4	5,564.4	3,929.3	7,199.5	29
Total population		253.1	3,338.4	5,598.9	7,967.1	6.260.4	9,673.8	21
C. hybrid								
Males	< 110			47.5	27.8	11.8	43.8	37
	> 109			33.8	16.5	11.3	21.7	32
Total males				81.3	44.3	27.4	61.2	38
Females	< 65			190.8	1.1	.5	1.7	55
	> 64			28.9	13.9	10.8	17.0	22
Total females				219.7	15.0	11.9	18.1	21
Total population				301.0	59.3	42.2	76.4	29

* mm, carapace width.

Table 3-.--Population estimates of *Chionoecetes bairdi* at different size limits in the Eastern Bering Sea based on RV *Oregon* survey in 1976.

Carapace Width (mm)	Numbers in Millions		Biomass in Thousand Tons	
	Males	Females	Males	Females
All Sizes	426.35	395.04	222.8	70.0
≥ 100	255.08	54.76	207.5	19.0
≥ 105	240.77	21.00	202.9	8.2
≥ 110	227.84	7.14	198.2	3.1
≥ 115	213.55	1.17	192.1	.6
≥ 120	198.60	.08	184.8	0
≥ 125	180.16	0	174.6	0
≥ 130	157.81	0	160.5	0
≥ 135	135.18	0	144.5	0
≥ 140	109.43	0	124.0	0
≥ 145	88.73	0	105.6	0
≥ 150	64.32	0	82.0	0
≥ 155	43.86	0	59.0	0
≥ 160	26.15	0	37.5	0

In this regard, Table 4 provides the 1976 population break-down into three stages of sexual maturity: immature, newly matured, and previously matured crabs. Assuming that both the immature and newly matured groups must be given some protection, one can see that these two groups combined as a percentage of the entire population beyond a certain minimum size in 1976 were as follows:

Minimum size limits	Immatures and Newly Matured *C. bairdi* as Percentage of biomass
100 mm	22
105	20
110	19
115	17
120	16
125	13
130	9
135	6
140	3
145	0

The tabular information above shows that if a minimum size limit for *C. bairdi* was set at 140 mm carapace width, then out of all those males subject to exploitation, only 3 percent of them are either immature or newly matured. Since it is inconceivable that the fishery will take 100 percent of all males greater than 140 mm, it means that the percentage (or numbers) of immature or newly matured crabs actually taken in the fishery will be lowered by the rate of exploitation. If the rate of exploitation was 30 percent, then only 37,200 mt (30 percent of 124,000 mt from Table 3) male *C. bairdi* will actually be taken. Out of this 37,200 mt of crabs, only 1,200 mt (30 percent of 4,043 mt from Table 4) of them were either immature or newly matured males. The rest were previously matured male crabs that are not as crucial for reproductive purposes.

Table 4.--Population estimates of male (A) Chionoecetes bairdi and (B) Chionoecetes opilio at different stages of maturity and minimum size limits in the eastern Bering Sea based on RV Oregon survey in 1976.

Carapace width (mm)	Population Numbers (millions)			Population Biomass (tons)		
	Imm*	New**	Previous***	Imm*	New**	Previous***
(A) Chionoecetes bairdi						
≥ 100	51.2	32.1	180.8	23,600	21,194	162,690
≥ 105	39.7	31.6	178.5	19,930	21,039	161,956
≥ 110	30.7	30.8	175.4	16,590	20,747	160,809
≥ 115	22.4	28.6	171.6	13,062	19,798	159,210
≥ 120	15.5	27.2	164.9	9,725	19,113	155,945
≥ 125	9.3	22.5	157.5	6,257	16,484	151,813
≥ 130	4.2	14.3	148.5	3,042	11,317	146,154
≥ 135	1.2	9.1	134.0	942	7,646	135,895
≥ 140	0	4.6	113.9	0	4,043	119,970
≥ 145	0	0	97.7	0	0	105,634
(B) Chionoecetes opilio						
≥ 100	3.9	17.0	260.6	1,781	8,506	174,225
≥ 105	.6	5.9	220.3	292	3,569	156,324
≥ 110	0	2.2	181.1	0	1,639	136,106
≥ 115	0	2.2	130.5	0	1,639	106,005
≥ 120	0	2.2	88.5	0	1,639	77,371
≥ 125	0	0	53.0	0	0	51,229

* Immature
** Newly Matured
*** Previously Matured

Note: Table summarized from Appendices 3 and 4.

Chionoecetes opilio

Based on the 1975 OCSEAP survey, which covered a larger area than the RV Oregon survey of 1976, it is surmised that a large percentage of the C. opilio population lay outside the survey area and was not estimated in the 1976 survey. Therefore the 1976 estimates of male opilio (2.4 billion, 459 thousand tons) and female opilio (5.6 billion, 360 thousand tons) are considered minimum estimates of population size (Appendix 2).

As in the case of C. bairdi (Table 3), the cumulative 1976 population sizes beyond a range of selected size limits for C. opilio are provided in Table 5. If one wants to determine minimum size regulation and allowable yields from these biomass estimates, one will have to consider the sexual maturity of the population (Table 4). Again, assuming that both the immature and newly matured groups need protection from exploitation, their combined percentage of the entire population beyond the range of minimum sizes is noted as:

Minimum size limit	Immatures and Newly Matured C. opilio as Percentage of biomass
100 mm	6
105	3
110	2
115	2
120	3
125	1

The tabular information above is used in conjunction with Tables 3 and 5 to evaluate the degree of protection given C. opilio male crabs for reproductive purposes as noted in the previous example for C. bairdi. It is apparent here that the 140 mm minimum size limitation imposed theoretically for C. bairdi has a different effect on C. opilio. With C. opilio, no males exceeding 140 mm that are either immature or newly matured are subject to exploitation. Therefore the special protection offered to these groups is 100 percent.

Table 5.--Population estimates of *Chionoecetes opilio* at different size limits in the Eastern Bering Sea based on RV *Oregon* survey in 1976.

Carapace width (mm)	Numbers in Millions		Biomass in Thousand Tons	
	Males	Females	Males	Females
All sizes	2,402.4	5,564.5	458.6	360.3
≥ 100	279.8	.1	185.3	.5
≥ 105	225.0	0	161.0	0
≥ 110	181.6	0	138.5	0
≥ 115	131.0	0	108.4	0
≥ 120	89.0	0	79.8	0
≥ 125	53.3	0	52.0	0
≥ 130	25.8	0	27.8	0
≥ 135	10.4	0	12.5	0
≥ 140	1.7	0	2.7	0
≥ 145	1.0	0	1.8	0
≥ 150	.8	0	1.4	0
≥ 155	.4	0	.9	0
≥ 160	.3	0	.8	0

TRADEOFFS INVOLVED WITH SETTING A MINIMUM SIZE LIMIT

A population is always undergoing some changes and heading towards some equilibrium conditions. The closer it is towards equilibrium, the more stable the populations will be, thereby allowing a more consistent pattern of exploitation without great fluctuations in the populations. This ideal case never happens--recruitment varies, population structure changes, mortality and reproduction schedules alter, and even the carrying capacity of the ecosystem changes--to name just a few of the variables that can disrupt equilibrium conditions.

The Tanner crab populations in the Eastern Bering Sea, given whatever conditions exist at present, are constantly undergoing changes in character and abundance. One would like to predict three things: (1) toward what equilibrium condition the present population trend is heading, (2) what some of the important changes in the present population would be given different exploitation strategies under current conditions, and (3) what changes in the population can be anticipated in the near future.

Equilibrium Conditions

Equilibrium conditions for *C. bairdi* and *C. opilio* have been inferred from Y/R theory. Equilibrium yield and biomass, however, are computed for *C. bairdi* only, because reliable recruitment estimates are not available for *C. opilio*. Based upon the eumetric fishing concept, it appears that it is rational to harvest male *C. bairdi* when it is about 123 mm carapace width (9.3 years old) at a reasonable fishing intensity ($F = 0.6$) to achieve a high value for Y/R when $M = 0.2$ (Figure 8). Table 1 shows equilibrium yield, equilibrium biomass of the harvestable population, and eumetric fishing mortality as functions of age and size of entry into the fishery.

Since the entries in the Table were based on the assumption of $M = 0.2$, the resulting optimum annual exploitation rate is approximately equal to 0.41. Thus, at equilibrium, 41% of the biomass of crabs larger than 123 mm could be harvested each year. Using the estimated average recruitment of four year old males (93,500,000) the expected annual equilibrium yield is about 18,000 metric tons and the equilibrium biomass is 43,500 metric tons.

Present Conditions

The 1976 biomass for male *C. bairdi* larger than 123 mm was approximately 180,000 mt (Table 3). In this case the equilibrium biomass is roughly one quarter of the present biomass. If the equilibrium exploitation rate (0.41) as suggested by Y/R theory were applied to the present biomass, then approximately 73,800 mt could be safely harvested in 1977.

Results of this example depend upon the assumption that future recruitment would not be affected by the specified minimum size and exploitation rate. If the minimum size and harvest rate are chosen such that the reproductive potential of the populations remains high, then the above changes will proceed until some equilibrium is reached. Since the number of recruits entering the fishery each year is quite variable, the actual age distribution and harvestable biomass which exist each year may deviate from equilibrium values; however over a sufficiently long timespan they will, on the average, tend to the equilibrium values.

If the assumption of constant average recruitment is incorrect and in fact lower in recent years, as previously estimated, the resulting equilibrium yield may be much less than anticipated. At present not enough is known about the relationship between the size of the spawning stock and future recruitment to predict how any exploitation scheme might affect recruitment. A conservative approach, which we feel is certainly justified under the present conditions, is to choose some scheme which insures the mature female population of complete insemination.

Figure 12 can be used to obtain a qualitative 8-year estimate of how a specific minimum size and exploitation rate may affect the ability of the surviving males to fertilize the mature female population. Returning to the above example, a minimum size of 123 mm would completely protect 32% of the newly matured males. The remaining 68% would be subjected to an exploitation rate of 41%, and consequently it would be expected that 28% of the newly matured males would actually be harvested. The actual numbers of these males taken in 1976 can be computed from Table 4.

The most obvious question at this point is how a removal of 28% of the male spawning stock will affect the chances of a maturing female finding a mate. One indicator of this is the resulting sex ratio of newly matured crabs. From 1969 to 1975, newly matured females were approximately 1.5 times as abundant as newly matured males. Using this as a reference, the expected sex ratio under the above conditions would be $1.5/(1.0 - 0.28) = 2.08$. Thus, with a 28% removal of males, the sex ratio is changed roughly to 2 newly matured females for every newly matured male. The actual effect of this change cannot be estimated because it is not known how many females a male can be expected to fertilize under natural conditions.

In the above example, a minimum size was set with the objective of obtaining some optimum yield, then the effects of the size limit on recruitment were explored. The process may be reversed: first a size limit which gives adequate protection to the spawning stock can be chosen, then the expected yield can be estimated. One example of this approach is to set a minimum size limit at 140 mm, a size which gives nearly complete protection to the newly matured males. To maintain a high yield, the exploitation rate would have to increase to approximately 60-70%. This is quite understandable, because as the biomass available for harvest is reduced by increasing the minimum size, maintaining a specified yield requires the legal-sized crabs to be harvested more intensively. Such high exploitation rates may not be economically feasible to maintain, thus there may be a decrease in yield.

Another factor to be considered is that as the minimum size increases, the fishery is directed toward fewer year classes. Any fluctuation in year class strength will then result in a concurrent fluctuation in annual harvest. This effect may be more important to the fishery than any decrease in yield.

The number of year classes that make up the fishable population above the 140 mm minimum size regulation is not known. If the occurence of double skip-molt crabs is as common in the eastern Bering Sea as it is in the Gulf of Alaska, then there may be at least 3 year classes in the eastern Bering Sea fishable population. If this is true, then fluctuations in annual harvest as a result of declining year class strength may be slightly dampened. It appears, however, that there may be substantial biological waste because not only are the older crabs apparently past their prime in reproduction, they also do not grow much in size and are reduced in numbers due to higher than normal natural mortality rates.

YEAR CLASS VARIABILITY AND ITS EFFECT ON THE FISHERY

Chionoecetes bairdi

Recruitment of 4 year old male *C. bairdi* into the population during 1971-75 (which came from corresponding year classes 1967-71) is shown in Figure 13. The results indicate that year class strength has been declining steadily from 1967 through 1971 as depicted by the decline in millions of 4 year olds as follows: 162 (1971), 133 (1972), 92 (1973), 52 (1974), and 28 (1975).

At present, the large year classes (1967-68) are entering a fishable size range (above 123 mm at age 9) although the bulk of recent catches (crabs above 140 mm at age 11) came from the 1965 and 1966 year classes. Since these catches were high, it is surmised that the 1965-66 year classes were probably rather large. It is also surmised that the harvestable population, though declining in trend, will be quite large through 1978. The small year classes (1970-71) will enter the fishery in the early 1980's, or even sooner, and a reduced harvest can be anticipated then.

In anticipation of the declining recruitment into the fishery that is expected in a few years, one may wish to examine the following management alternatives while taking into account the effects of minimum size regulation on yield and reproductive potential:

(1) Use recruitment strength as a criterion for setting catch levels. This alternative would result in great fluctuations in annual yields, and consequently be undesirable economically to the fishing industry.

(2) Keep annual yields stabilized by harvesting fewer crabs than possible when recruitment is high, and more crabs than biologically possible when recruitment is low (as is expected to be the case

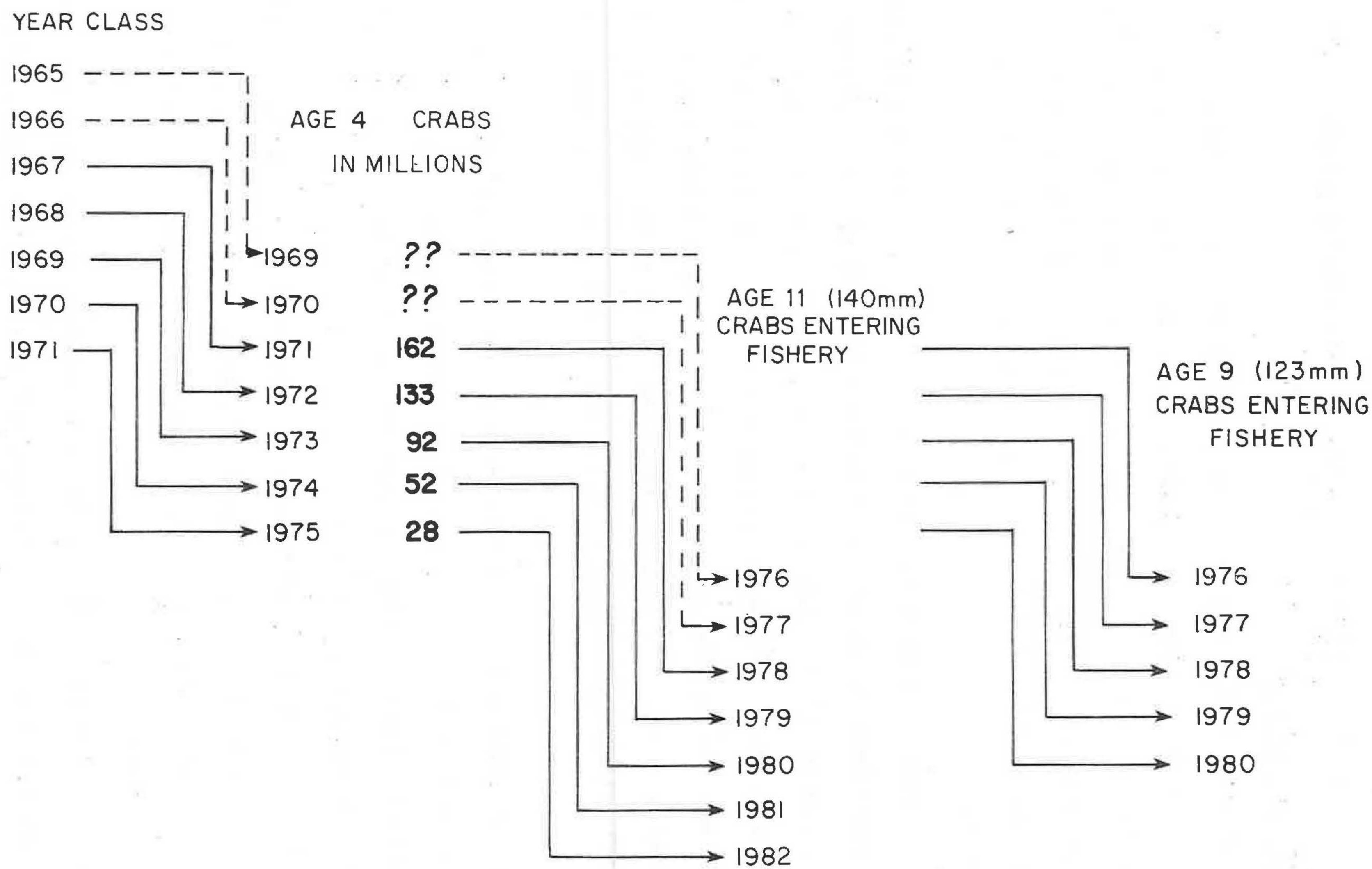


Figure 13. Year class strengths of male Chionoecetes bairdi and their principal years of entry into the fishery.

in the early 1980's). This strategy is inherently biologically "wasteful", however, because the large crabs left over in high recruitment years will decrease in numbers due to natural mortality, and also apparently do not contribute greatly to the reproductive success of the population.

(3) Shift the geographical location of the fishery northwards in order to increase the utilization of *C. opilio*.

(4) Lower the minimum size limitation. This would have two effects. It would (a) spread the harvest over more age groups than are currently being exploited, and (b) shift some of the burden of exploitation to *C. opilio*, which is currently being underutilized. A lower minimum size limitation appears to be justifiable based upon Y/R theory. At the same time, the catch limit should also be set at levels which take into account the expected decline in recruitment of *C. bairdi*.

Chionoecetes opilio

Fluctuations in year class strength is apparently more pronounced for *C. opilio* than for *C. bairdi*. Two strong year classes, one that is presently about 90 mm wide and another about 50 mm wide, will be entering the fishery in several years. Over the years 1969-1976, the conspicuous difference between these two Tanner crab species in the Bering Sea has been that *C. opilio* has a much more variable recruitment. Although at present the available data is quite meager, it appears *C. opilio* match the timing of their larvae release with the spring bloom associated with the receding ice pack, while *C. bairdi* release their larvae later in response to the normal spring bloom associated with thermal stratification of the water column. The second spring bloom may produce optimal conditions more often and consequently the larvae of C. bairdi will have a better chance of survival than those of C. opilio in the long run. An important aspect of this difference is that species which display a "pulse" type recruitment pattern similar to C. opilio are more vulnerable to a population failure due to recruitment overfishing.

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Appendix 1. POPULATION ESTIMATES OF CHIONOECETES BAIRDI IN THE EASTERN BERING SEA BASED UPON NMFS SURVEYS IN 1976

CARAPACE WIDTH(MM)	POPULATION NUMBERS MALES	FEMALES	BIOMASS IN TONS MALES	FEMALES
5- 9	56418	95605	0	0
10- 14	570135	310406	0	0
15- 19	1973672	1304605	2	2
20- 24	7350374	5709497	20	16
25- 29	11805925	14062102	61	73
30- 34	13401943	17457033	161	153
35- 39	9378093	9471086	129	130
40- 44	13584142	14175583	277	289
45- 49	14203462	17665877	410	510
50- 54	4953432	6444559	196	254
55- 59	4907368	7603986	258	399
60- 64	7657657	5241082	522	357
65- 69	7963664	8627935	690	747
70- 74	12244369	19708701	1325	2134
75- 79	13511095	19371345	1301	2582
80- 84	8233262	27402003	1334	4439
85- 89	10334931	44247578	2011	8610
90- 94	11280774	67161288	2610	15540
95- 99	12359232	54221440	3506	14732
100-104	14308377	33756627	4558	10754
105-109	12932949	13858855	4779	5121
110-114	14288995	5974444	6082	2543
115-119	14951728	1039900	7237	531
120-124	18435795	79545	10229	44
125-129	22346192	0	14042	0
130-134	22631962	0	16030	0
135-139	25755123	0	20469	0
140-144	20693942	0	18379	0
145-149	23911613	0	23641	0
150-154	20957025	0	22983	0
155-159	17715870	0	21478	0
160-164	13110119	0	17516	0
165-169	9203940	0	13511	0
170-174	2425007	0	3901	0
175-179	939466	0	1652	0
180-184	235817	0	452	0
185-189	175729	0	366	0
190-194	59259	0	134	0
TOTAL	426348356	395041082	222801	70010

Appendix 2. POPULATION ESTIMATES OF *CHIONOECETES OPILIO* IN THE EASTERN BERING SEA BASED UPON NMFS SURVEYS IN 1976

CARAPACE	POPULATION NUMBERS		BIOMASS IN TONS	
WIDTH(MM)	MALES	FEMALES	MALES	FEMALES
20- 24	11010985	10733944	40	39
25- 29	9602060	224567	67	2
30- 34	99587354	102561690	1176	1211
35- 39	187664901	241500949	3490	4491
40- 44	181765786	659073588	5026	13223
45- 49	196469039	1112750480	7724	43748
50- 54	139098711	1129383653	10201	60926
55- 59	135496143	956703513	13337	63788
60- 64	148548166	654128692	13896	61190
65- 69	122891081	291042363	14654	34705
70- 74	117153496	260341776	17499	33961
75- 79	91959504	124084781	16947	22868
80- 84	132361283	16203767	29701	3636
85- 89	193765541	3648643	53678	985
90- 94	158093012	1438066	50853	463
95- 99	92173116	69847	34989	27
100-104	54746937	106286	24322	47
105-109	43484021	0	22440	0
110-114	50561986	0	30101	0
115-119	41952920	0	28634	0
120-124	35707564	0	27781	0
125-129	27489822	0	24252	0
130-134	15382410	0	15314	0
135-139	8712538	0	9744	0
140-144	706569	0	884	0
145-149	282619	0	394	0
150-154	317912	0	492	0
155-159	86957	0	149	0
160-164	0	0	0	0
165-169	219846	0	457	0
170-174	42613	0	97	0
175-179	42613	0	106	0
180-184	0	0	0	0
185-189	43917	0	130	0
TOTAL	2402421932	5564502105	453574	360308

Appendix 3.--Population estimates of male Chionoecetes bairdi at different stages of maturity in the eastern Bering Sea based on RV Oregon survey in 1976.

Carapace width (mm)	Population Size Numbers (Millions)	Population Size Biomass (Tons)	Ratio Imm*	Ratio New**	Ratio Previous***	Population Numbers (Millions) Imm	Population Numbers (Millions) New	Population Numbers (Millions) Previous	Biomass in Tons Imm	Biomass in Tons New	Biomass in Tons Previous
60-64	7.7	522	1.000			7.7			522.0		
65-69	8.0	690	1.000			8.0			690.0		
70-74	12.2	1325	1.000			12.2			1325.0		
75-79	13.5	1801	0.990	0.010		13.4	0.1		1783.0	18.0	
80-84	8.2	1334	.995	.003	.003	8.2	0.0	0.0	1327.3	4.0	4.0
85-89	10.3	2011	.981	.010	.010	10.1	0.1	0.1	1972.8	20.1	20.1
90-94	11.3	2610	.948	.025	.028	10.7	0.3	0.3	2474.3	65.3	73.1
95-99	12.9	3506	.889	.050	.061	11.5	0.7	0.8	3116.8	175.3	213.9
100-104	14.3	4558	.805	.034	.161	11.5	0.5	2.3	3669.2	155.0	733.9
105-109	12.9	4779	.699	.061	.240	9.0	0.8	3.1	3340.5	291.5	1147.0
110-114	14.3	6082	.580	.156	.263	8.3	2.2	3.8	3527.6	948.8	1599.6
115-119	15.0	7287	.458	.094	.448	6.9	1.4	6.7	3337.5	685.0	3264.6
120-124	18.4	10229	.339	.257	.404	6.2	4.7	7.4	3467.6	2628.9	4132.5
125-129	22.4	14042	.229	.368	.403	5.1	8.2	9.0	3215.6	5167.5	5658.9
130-134	22.6	16030	.131	.229	.640	3.0	5.2	14.5	2099.9	3670.9	10259.2
135-139	25.8	20469	.046	.176	.778	1.2	4.5	20.1	941.6	3602.5	15924.9
140-144	20.7	18379	.000	.220	.780	0.0	4.6	16.2	0	4043.4	14335.6
145	97.7	105634	.000	.000	1.000	0	0	97.7	0	0	105634.0

* Immature
** Newly Matured
*** Previously Matured

Appendix 4.--Population estimates of male <u>Chionoecetes opilio</u> at different stages of maturity in the eastern Bering Sea based upon NMFS surveys in 1976.

Carapace width (mm)	Population Size Numbers (Millions)	Population Size Biomass (Tons)	Ratio Imm*	Ratio New**	Ratio Previous***	Population Numbers (millions) Imm	Population Numbers (millions) New	Population Numbers (millions) Previous	Biomass in Tons Imm	Biomass in Tons New	Biomass in Tons Previous
40-44	181.8	5026	0.971	0.025	0.004	176.5	4.6	0.7	4880.3	125.7	20.1
45-49	196.5	7724	.932	.061	.006	183.1	12.0	1.2	7198.8	471.2	46.4
50-54	189.1	10201	.874	.049	.077	165.3	9.3	14.6	8915.7	499.9	785.5
55-59	185.5	13337	.799	.041	.160	148.2	7.6	29.7	10656.3	546.8	2133.9
60-64	148.5	13896	.711	.139	.150	105.6	20.6	22.3	9880.1	1931.5	2084.4
65-69	122.9	14654	.615	.228	.156	75.6	28.0	19.2	9012.2	3341.1	2286.0
70-74	117.2	17499	.518	.269	.213	60.7	31.5	25.0	9064.5	4707.2	3727.3
75-79	92.0	16947	.424	.241	.335	39.0	22.2	30.8	7185.5	4084.2	5677.3
80-84	132.4	29701	.335	.235	.430	44.4	31.1	56.9	9949.8	6979.7	12771.4
85-89	198.8	53678	.254	.153	.594	50.4	30.4	118.1	13634.2	8212.7	31884.7
90-94	158.1	50853	.175	.000	.825	27.7	0.0	130.4	8899.3		41953.7
95-99	92.2	34989	.117	.052	.831	10.8	4.8	76.6	4093.7	1819.4	29075.9
100-104	54.8	24322	.061	.203	.736	3.3	11.1	40.3	1483.6	4937.4	17901.0
105-109	43.5	22440	.013	.086	.901	0.6	3.7	39.2	291.7	1929.8	20218.4
110-114	50.6	30101	.000	.000	1.000			50.6			30101.0
115-119	42.0	28634	.000	.000	1.000			42.0			28634.0
120-124	37.7	27781	.000	.059	.941		2.2	35.5		1639.1	26141.9
125	53.0	51229	.000	.000	1.000			53.0			51229.0

* Immature
** Newly Matured
*** Previously Matured