Northwest and Alaska Fisheries Center Processed Report

DYNAMICS OF POLLOCK AND HERRING BIOMASSES IN THE EASTERN BERING SEA

(An introductory study of fluctuations of pollock and herring stocks using preliminary 8-component Dynamic Numerical Marine Ecosystem Model)

by

T. Laevastu and F. Favorite
Resource Ecology Task
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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest and Alaska Fisheries Center
2725 Montlake Boulevard
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ABSTRACT

An 8-component submodel of a rather complete dynamic numerical marine ecosystem (DYNUMES) model was used to investigate some aspects of pollock and herring biomass dynamics in the eastern Bering Sea. Results indicate that cannibalism by older pollock is a major factor in biomass fluctuations and can induce long-term biomass cycles that are also affected by the fishery and consumption by mammals. The model shows that relatively intensive fishery on pollock, which removes older, more cannibalistic fish, is beneficial for pollock stock, and that the optimum annual pollock harvest is slightly above 1 million tons. This is the case with specified conditions and for the specified time period included in the present analysis. The pollock harvest in some years may increase or decrease depending upon the strength of year classes which is to say good or bad survival of pollock to recruitment size which may be a function of physical environmental factors as well as the mortality from cannibalism. Juvenile pollock, as well as herring and other forage fishes, suffer from low abundances of zooplankton and periods of low abundance of juvenile pollock markedly affects the grazing pressure on herring.

I. THE OBJECTIVES OF THE NUMERICAL STUDY

It has long been recognized that the productivity of any marine resource is a complex function of the synergism between species and stocks and their physical and biological environmental as well as intra-stock (or intra-species) interactions. Ideally, production models for any species should consider the totality of these interactions. These ecological relationships are, however, extremely complex and difficult to describe, let alone quantify. Moreover, since most of the processes are beyond human control, the pragmatic necessity for resource management has resulted in the evolution of yield models developed around the one controllable source of mortality, the quantity and quality of fishing effort. The conventional models deal with single species and express yield principally in terms of the resultants of population increments (recruitment and growth) and decrements (natural and fishing mortality), with almost total disregard for the ecological processes which determine these population parameters.

Single species management models have provided and will continue to provide a basis for rational management decisions. Current and future decisions concerning marine resources, even for the management of single species, will require a basis for short and long term forecasts of yield which gets beyond the scope of the conventional single species models and requires a better understanding of the interaction of any species with its physical and biological environment. Furthermore, the scope of pressing marine resource management decisions has increased beyond considerations of fisheries alone and includes assessment of the effects of fishing not only on target species but on other animals in the community, including not only fishes but commercially important invertebrates, mammals and birds as well.

In the course of developing a Dynamical Numerical Marine Ecosystem (DYNUMES) model for the eastern Bering Sea, many relevant fisheries results (and/or outputs) were obtained with an 8-component ecosystem submodel. Although the model is far from complete, it is the most comprehensive and complex of its kind available anywhere, and provides insights into many of the interactive processes in the marine ecosystem, as well as, on the effects of a fishery on a given species as well as on ecologically (e.g., through predator-prey relations) related species. Results from the use of this model can serve as the basis for further research and verification with empirical data.

The three computer runs with this submodel, described in this report, were made specifically to study:

1. The effects of different levels of fishing effort on pollock population.

2. The trophodynamic interactions within the pollock population as well as interaction with the herring population (as one of the prey items for pollock).

3. The mechanisms (interactions) causing long-term fluctuations in abundance of pollock.

4. The effects of grazing by mammals (seals, sea lions) and fishing on spatial distribution of pollock (and, partially, on herring).

Although the results of these computer runs are not quantitatively precise, they indicate a number of conditions and processes which could form important bases for decisions related to fisheries management.

The authors express their sincere thanks to Dr. F. Fukuhara, Dr. L. L. Low and Mr. J. Hastings for many valuable suggestions and discussions in the course of preparation of this report. Thanks are also due to Mrs. M. Gregory for typing of the report and to Ms. E. Zweifel for its reproduction.

II. THE MODEL AND ITS INPUTS

The 8-component submodel of the Dynamic Numerical Marine Ecosystem (DYNUMES) model (Laevastu, Favorite and McAlister, 1976) is a three-dimensional ecosystem submodel for the eastern Bering Sea (see grid on Figure 1). The grid size is 95.25 km. The basic time step for advection functions is one week; in the trophodynamic subroutines the basic time step is one month.

The distribution and abundance of pollock and herring are prescribed for the first month-January. The pollock population size is the "minimum sustainable" within an 8-component model. As the submodel does not contain all organism groups which might graze upon pollock, the "minimum sustainable" population in this model is somewhat smaller than the real population in the Bering Sea. As the "minimum sustainable" herring population within the 8-component model for the eastern Bering Sea, 1 million tons was used in most runs. However, some runs with 1.5 million ton populations were also made and are reported in this paper. It should be noted that in this model (and in stomach analyses results in general) all fish included under herring are not necessarily all herring, and could include some capelin and/or smelt; but very little is known about the abundances of these two species in the Bering Sea.

The pollock biomass (population) is divided into three age (size) groups: group 1 is assumed to consist of prefishery juveniles (<25 cm length, <3 years; initial allocation 40.5% of total biomass); group 2 is assumed to consist of pollock 25 to 45 cm in length (*ca* 3 to 5 years; initial allocation 41.5% of total biomass); group 3 consists of older pollock >45 cm in length (>5 years; initial allocation 18% of total biomass). This division is somewhat arbitrary, as the actual

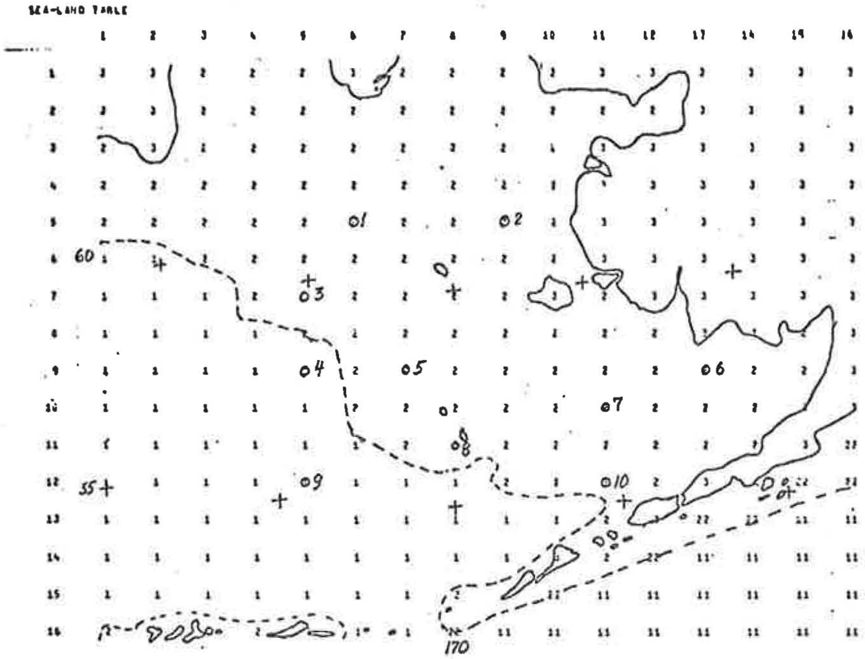


Fig. 1A.--Computation grid, computer printout form.

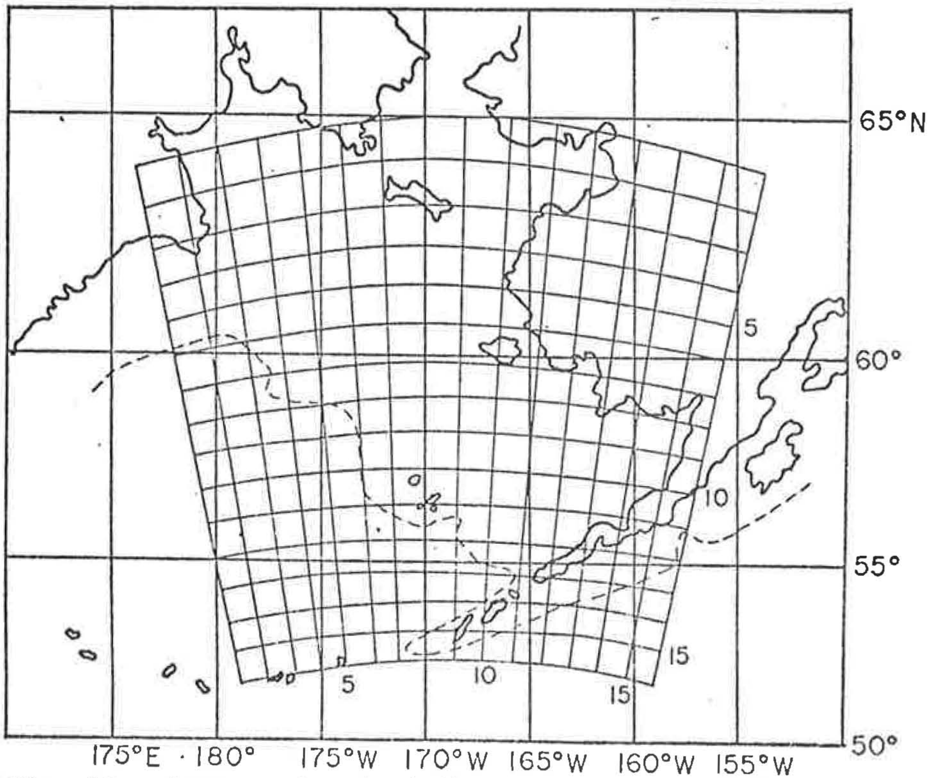


Fig. 1B.--Computation (model) grid for Eastern Bering Sea drawn on a Mercator projection.

quantities (biomass proportions in each age group) are not known and are derived using an indirect iterative procedure. Therefore, an initial adjustment is necessary in the model and takes place within the first year's computation. The herring population (biomass) is computed as one (all ages) group.

An average composition of food is assigned to each size group of pollock (Table 1). The change of food composition with age is one of the bases for the division of pollock into size groups (Figure 2), but the cannibalism programmed in the model is considerably less than that indicated by Takahashi and Yamaguchi (1972) (compare Figure 2 and Table 1). The effects of cannibalism on the dynamics of the pollock population are rather profound, but data on the spatial and temporal variation of cannibalism in pollock are scarce. Therefore, it was decided to model these effects with somewhat conservative data. Although the composition of food in the present model is unchangeable in space and time, this parameter will be made variable and a function of availability of different food items in future versions of the model.

The food coefficients used in the model are also relatively conservative (Table 2). The consumption of pollock and herring by mammals and birds is computed in specific subroutines. The consumption of herring and juvenile pollock by other fish (sablefish, flatfishes, etc.) is not taken into account, therefore, the total biomass of pollock is an underestimate and is considered the "minimum sustainable" biomass. The juvenile pollock biomass growth is decreased in the model when it reaches 3 million metric tons in the eastern Bering Sea. This limitation

Table 1.--Average composition of food for pollock and herring (as used in the model).

Species	Food Items	% by weight
Pollock, juveniles	Copepods	30
	Euphausids	70
	"Others"	10
Pollock, 25 to 45 cm	Copepods	18
	Euphausids	56
	Herring	10
	Pollock (juvenile)	8
	Benthos	6
	"Others"	2
Pollock >45 cm	Copepods	5
	Euphausids	30
	Herring	10
	Pollock (juveniles)	24
	Pollock (>25 cm)	10
	Benthos	16
	"Others"	5
Herring	Copepods	70
	Euphausids	20
	"Others"	10

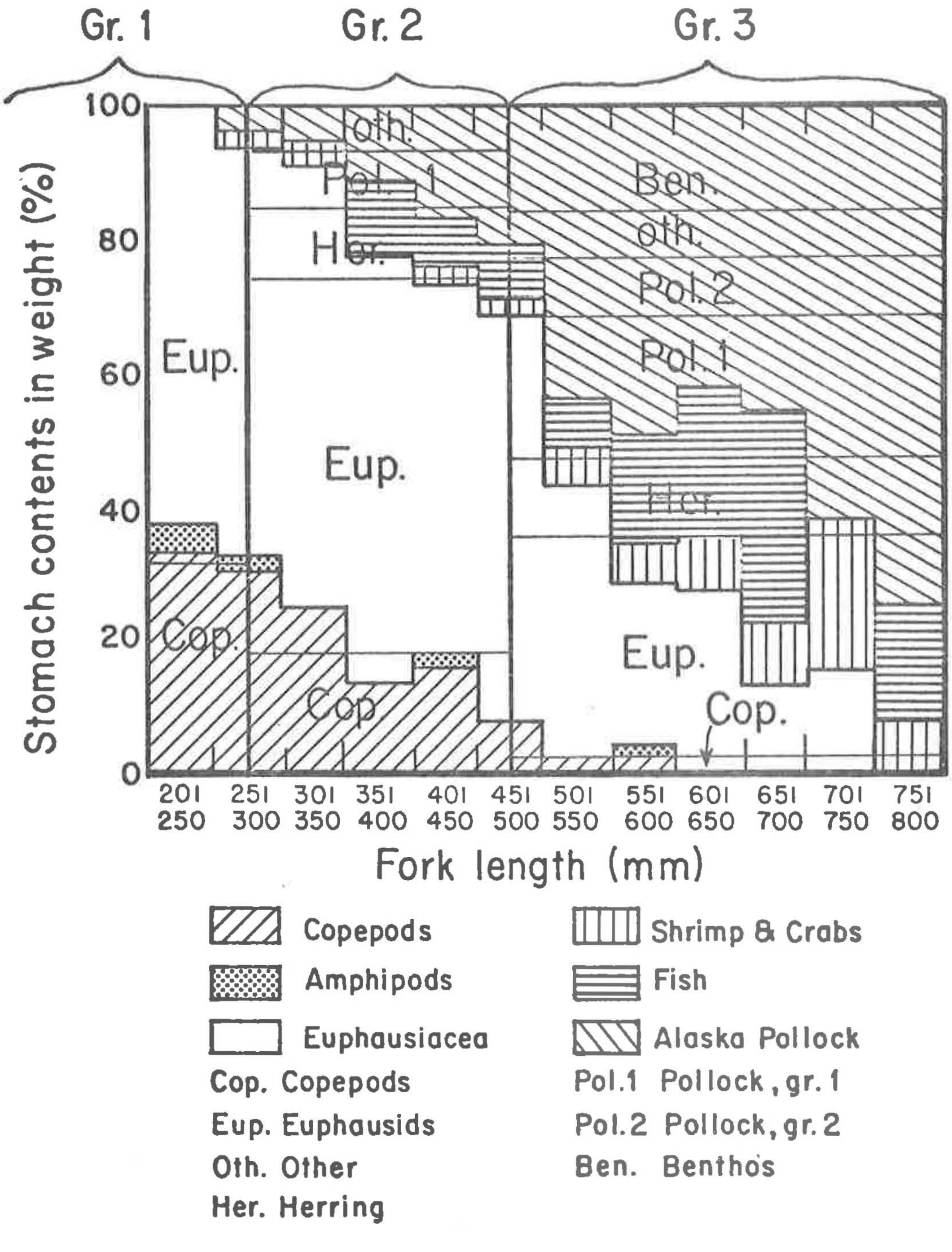


Figure 2.--Relation between pollock growth (expressed as fork length) and feeding preferences (Takahashi and Yamaguchi, 1972), (with indication of food composition as used in the model).

Table 2.--Food coefficients for growth and maintenance (as used in the model).

Species	Food coefficient for growth	Food for maintenace, % body weight daily
Herring	1:2.0	1.0
Pollock Gr. 1	1:2.2	1.1
Gr. 2	1:2.0	1.0
Gr. 3	1:1.9	0.93

is prescribed on the assumption that availability of food (copepods and euphausids) would become a limiting factor for this population (see further Laevastu, Dunn and Favorite, 1976).

It can be assumed that some "herring" reported in stomach analyses of pollock can be partly capelin and smelt, but very little is known about the abundance and distribution of these two species in the eastern Bering Sea. Therefore, the initial estimate of the herring population size might not reflect fully the true abundance of herring. The "minimum sustainable" herring population for the present model is ca 1.25 million metric tons; however, two different initial assumptions on the size of the herring biomass were used in the model: 1.5 million and 1 million tons.

The catches are computed with spatially and temporally varying fishing intensity coefficients. These coefficients were "tuned" to average annual catch during past few years (1.2 million tons for pollock and ca 50,000 tons for herring). These coefficients were decreased 20% and 50% respectively in other runs to study the effects of different fishing intensity on pollock and herring populations in the eastern Bering Sea.

Each pollock biomass group and herring biomass as a whole were assigned growth coefficients, which were "tuned" to sustain the prescribed biomass sizes (the principle of this computation is described in Laevastu and Favorite, 1976). The growth coefficients used in the present model (Table 3) and mean growth coefficients from actual measurements (Table 4) allow the computation of approximate mean ages of the selected

Table 3.--Bulk growth and mortality rates in % per month (as used in the model).

Species	Growth rate % per month	Mortality rate and/or consumption and remarks
Herring	9.0	Consumption by seals (2 species), birds (2 species), and pollock; fishery
Pollock, group 1	9.67	40% of total pollock consumption, 3.35% moved to groups 2 each month.
group 2	3.3	50% of total consumption, 2.75 moved to group 3 each month; fishery (42% of effort)
group 3	0.8	10% of total consumption, fishery (58% of effort), 1.58 of "natural" mortality

Note: Bulk growth rate (or biomass growth rate) is only indirectly comparable to individual species growth rate.

Table 4.--Monthly growth rates in % per month for herring and pollock (actual growth rates as ascertained from literature).

Age Interval Years	Herring [1]	Pollock [2]
1 to 2	6.35 to 7.08	10.83
2 - 3	2.57 to 3.09	5.69
3 - 4	1.74 to 1.88	3.03
4 - 5	1.29 to 1.53	2.14
5 - 6	0.82 to 0.95	1.69
6 - 7	0.82 to 0.99	1.22
7 - 8	0.56 to 0.60	1.20
8 - 9		1.11
9 - 10		0.92

[1] Fast growth in first year (ca 30 g). Upper and lower limits given.

[2] Growth in first year ca 50 g.

Note: Lower growth rate in herring applies to fish which had grown fast in first year and continues to grow fast.

size (age) groups. Through considerations of the average age in each group and the removal of fish from these groups by grazing and the fishery, it is possible to compute the approximate transfer of biomass from one group to another due to growth and aging. These transfer coefficients are also given (Table 3).

The biomasses at each grid point in the eastern Bering Sea are altered in weekly time steps with prescribed migration speeds and directions ascertained from numerous descriptive notes in the literature on the seasonal migrations of pollock and herring in the Bering Sea. The growth, grazing, fishery, and "old age" mortality is computed at each grid point in each monthly time step, and the individual biomasses at each grid point are summed each month to compute the total biomass in the eastern Bering Sea. This summation requires the assumption that there are no migrations through the boundaries into and out of the area. The eastern Bering Sea as outlined in the model (Figure 1) can, however, be considered a closed system. In this paper we are dealing mainly with the total biomass in the eastern Bering Sea and a few peculiarities in its spatial distribution. The main consideration centers on the effects of changing fishing effort on pollock, with notes on herring where called for. Further details of the model, not essential to the present paper, are found in Laevastu, Favorite and McAlister, 1976. The model undergoes continued refinements and enlargements, depending on results and research and application requirements.

III. LONG-TERM CHANGES OF POLLOCK BIOMASS IN THE EASTERN BERING SEA AND THE EFFECT OF FISHERY ON THESE CHANGES

The changes of the total biomass of pollock (prefishery as well as exploitable stock) in the eastern Bering Sea during a ten-year period while subjected to 3 fishing efforts is shown (Figure 3): Curve A presents the computation with the present fishing effort (*ca* 1.25 million caught annually), curve B is obtained using 80% of the present fishing effort, and curve C is obtained using 50% of present fishing effort. The following discussions deal mainly with curves A and C. With the present intensive fishery, the total pollock biomass decreases from about 5.1 million tons ("minimum sustainable" biomass, defined earlier) to about 4 million tons within one year. This decrease is due to two factors: first, removal of medium and large size pollock by fishery (see Figures 5 and 6), and, secondly, to internal model adjustment, as the initial estimate of biomass distribution between different age groups was apparently not in proper balance with prescribed fishery and with internal consumption in the ecosystem. The total pollock biomass remains relatively constant during the second year (Figure 3) with present fishery, whereas the medium size group of pollock still declines (Figure 5) and the size group of older fish shows only a slight increase in the second year (Figure 6). The prefishery juvenile group (Figure 4) starts to increase with present fishing effort after the first year. This increase is mainly due to a decrease in cannibalistic grazing on this size group by medium and large size pollock, which decreased during the first year.

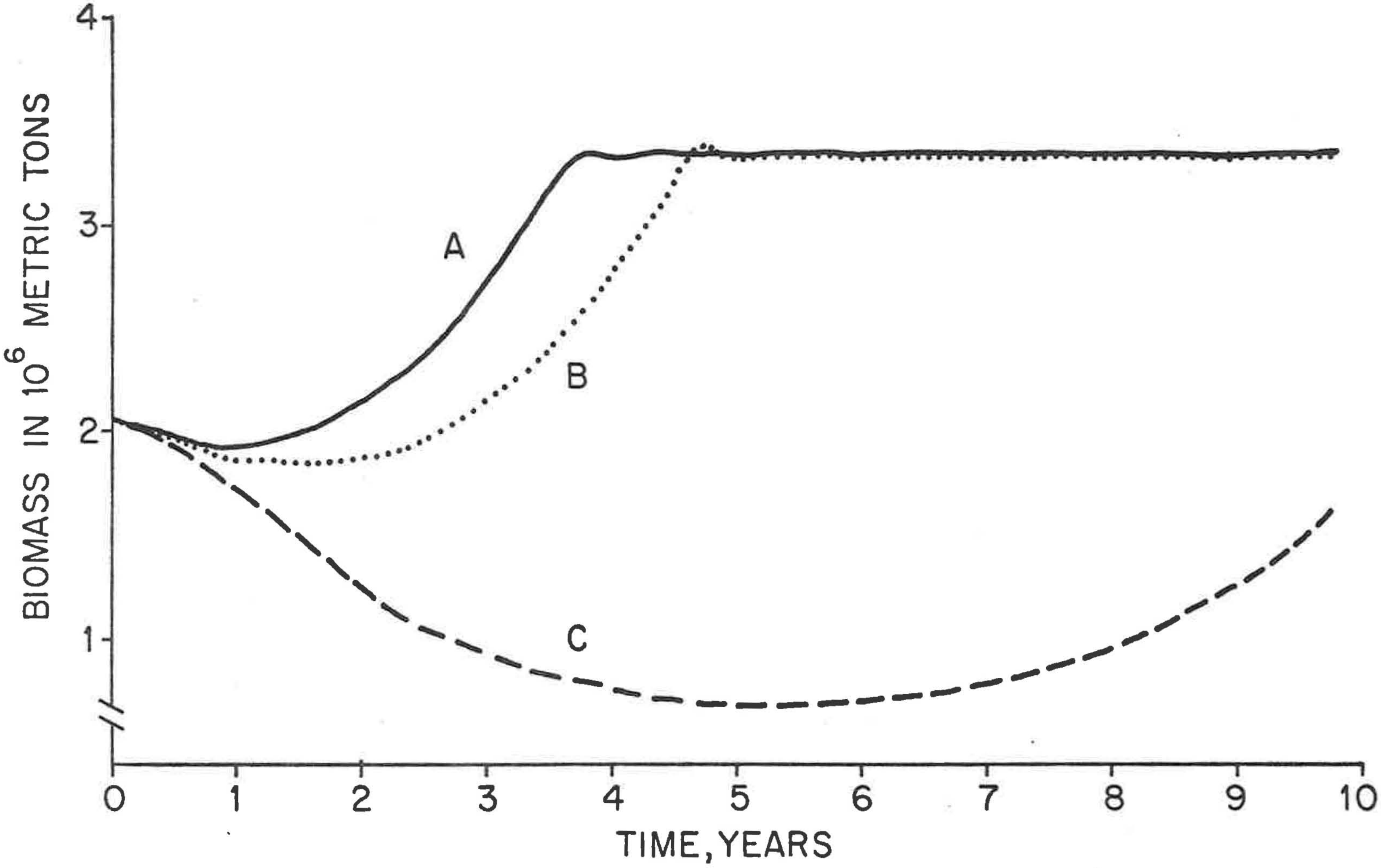


Figure 3.--Changes of total biomass of pollock in eastern Bering Sea, A.●—● present fishery; B. Δ----Δ 80% of present fishing effort; C. x——x 50% of present fishing effort.

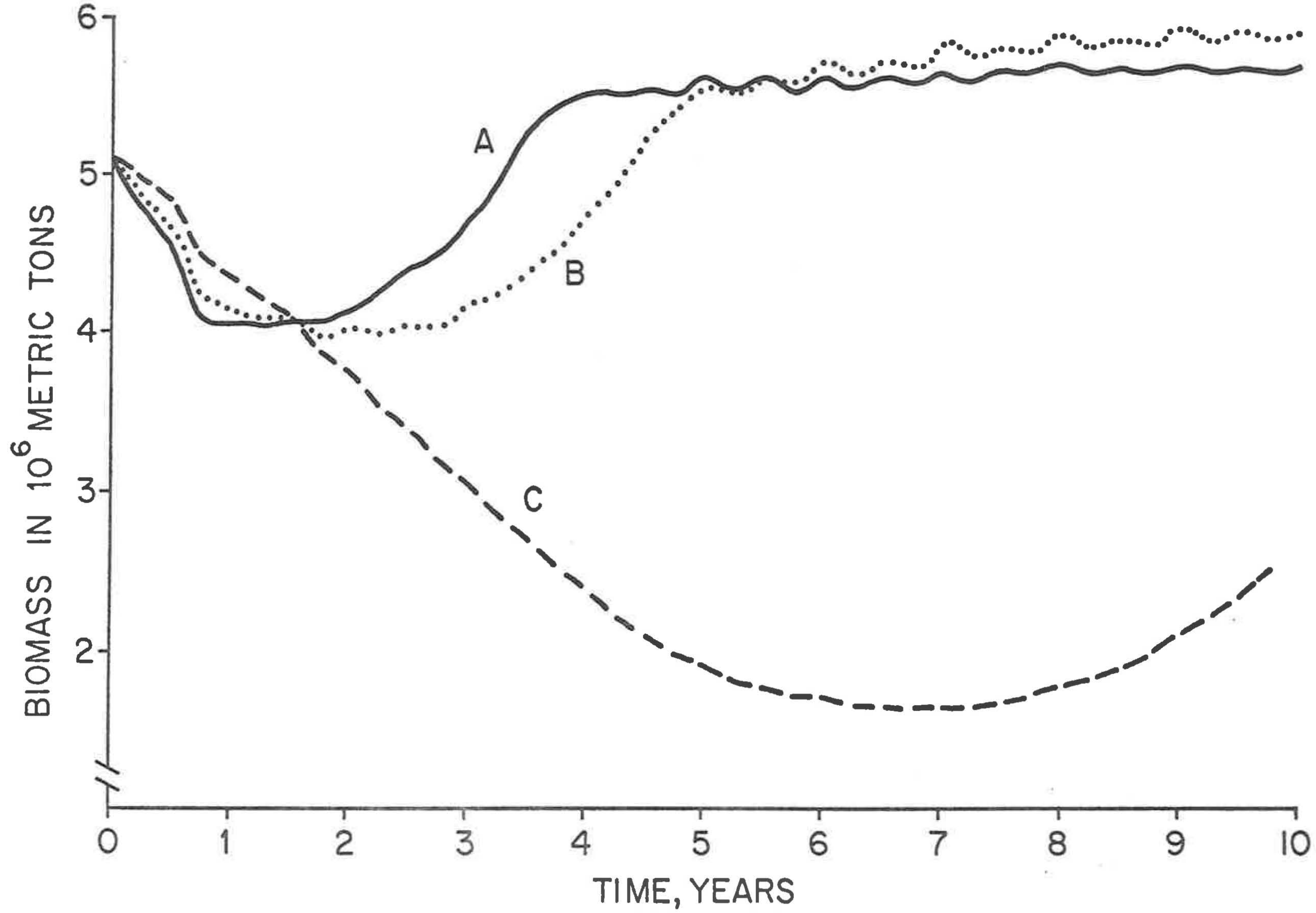


Figure 4.--Changes of juvenile pollock biomass in eastern Bering Sea. A. present fishery; B. 80% of present fishing effort; C. 50% of present fishing effort.

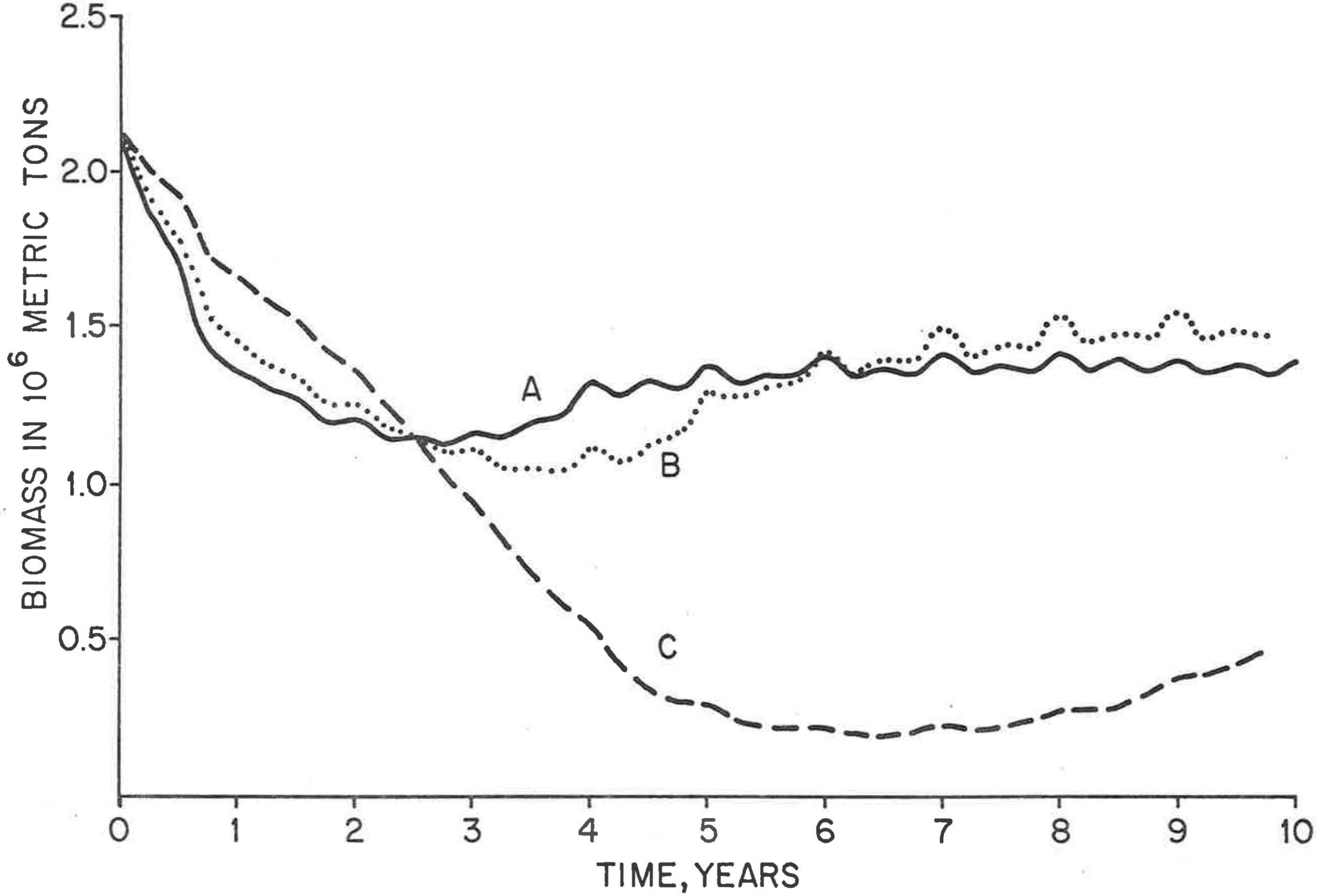


Figure 5.--Changes of medium size (25 to 45 cm) pollock biomass in eastern Bering Sea. A. present fishery, B. 80% of present fishing effort, C. 50% of present fishing effort.

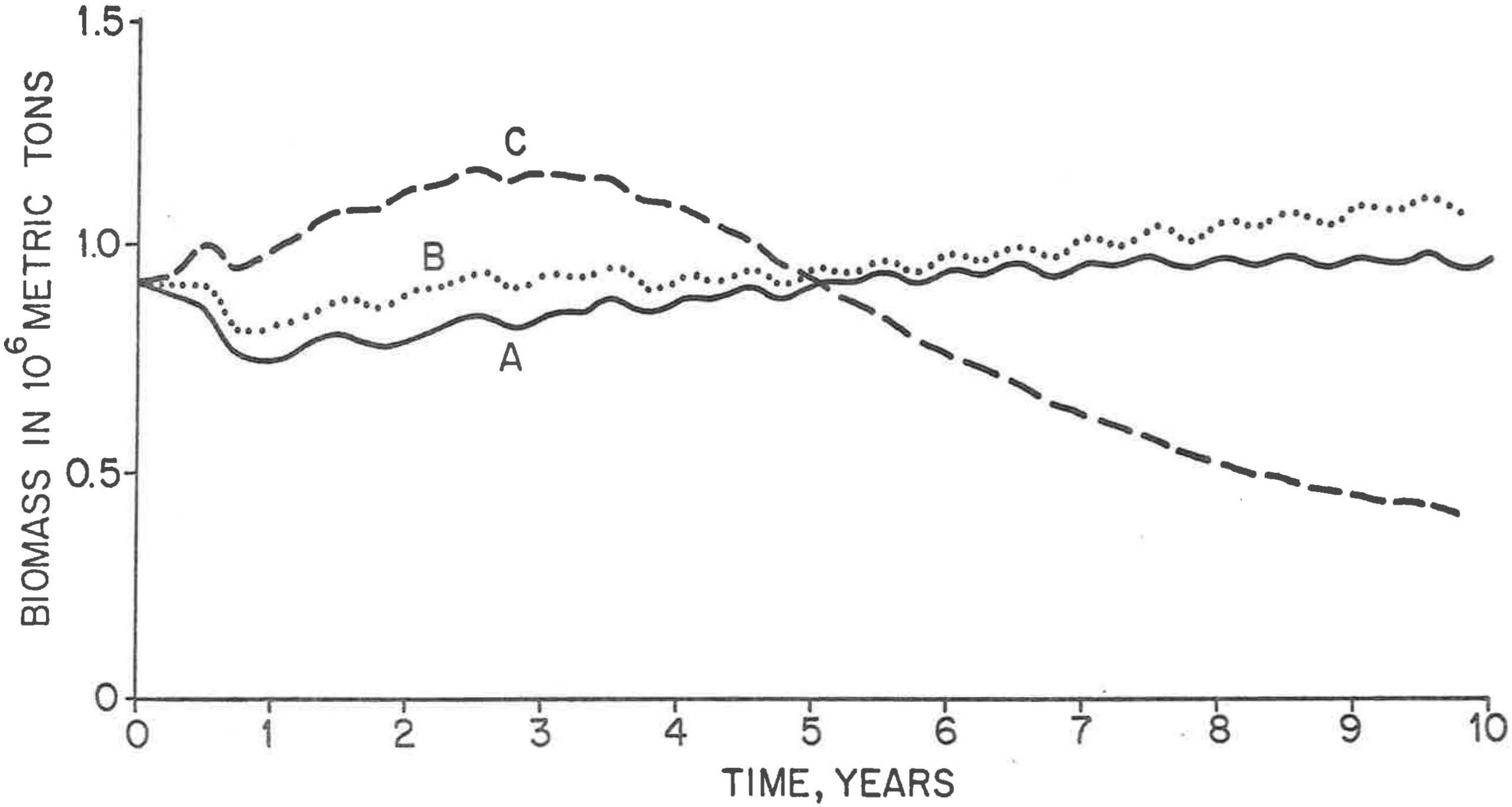


Figure 6.--Changes of old pollock (>45 cm) biomass in eastern Bering Sea. A. present fishery, B. 80% of present fishing effort, C. 50% of present fishing effort.

The biomass of the juvenile group continues to grow until the end of the third year (Figure 4, curve A), whereafter this biomass remains quasi-constant due to a limit set in the program for its growth. This limit was set with the assumption that availability of food becomes a limiting factor for a large population.

The medium size pollock biomass starts to grow after three years (due to recruitment from juvenile biomass), reaching a quasi-constant level after six years (Figure 5, curve A), whereas the older pollock reaches the quasi-constant level in about six and a half years (Figure 6). The fishery yield (Figure 7, curve A) with present fishing effort decreases considerably in the second year, remains about at the same low level in the third year, and starts to increase thereafter, reaching a quasi-constant level in the sixth year. This level (1.08 million tons) is less that the present fishery (1.25 million tons).

If present fishing effort is decreased by 50%, the model shows that the total biomass of pollock decreases for about five and one-half years whereafter an increase sets in (Figure 3, curve C). This initial decrease is due to increased cannibalistic grazing by increased biomass of old pollock (Figure 6, curve C). The increase in old pollock biomass stops after three years (Figure 6) and starts to decrease after three and one-half years due to decreased recruitment from medium size group (Figure 5, curve C). The latter is also decreasing because of decreased recruitment from a decreasing juvenile biomass. The medium size group decreases for about five and one-half years and starts to increase slightly after about seven and one-half years, due to increased recruitment. This

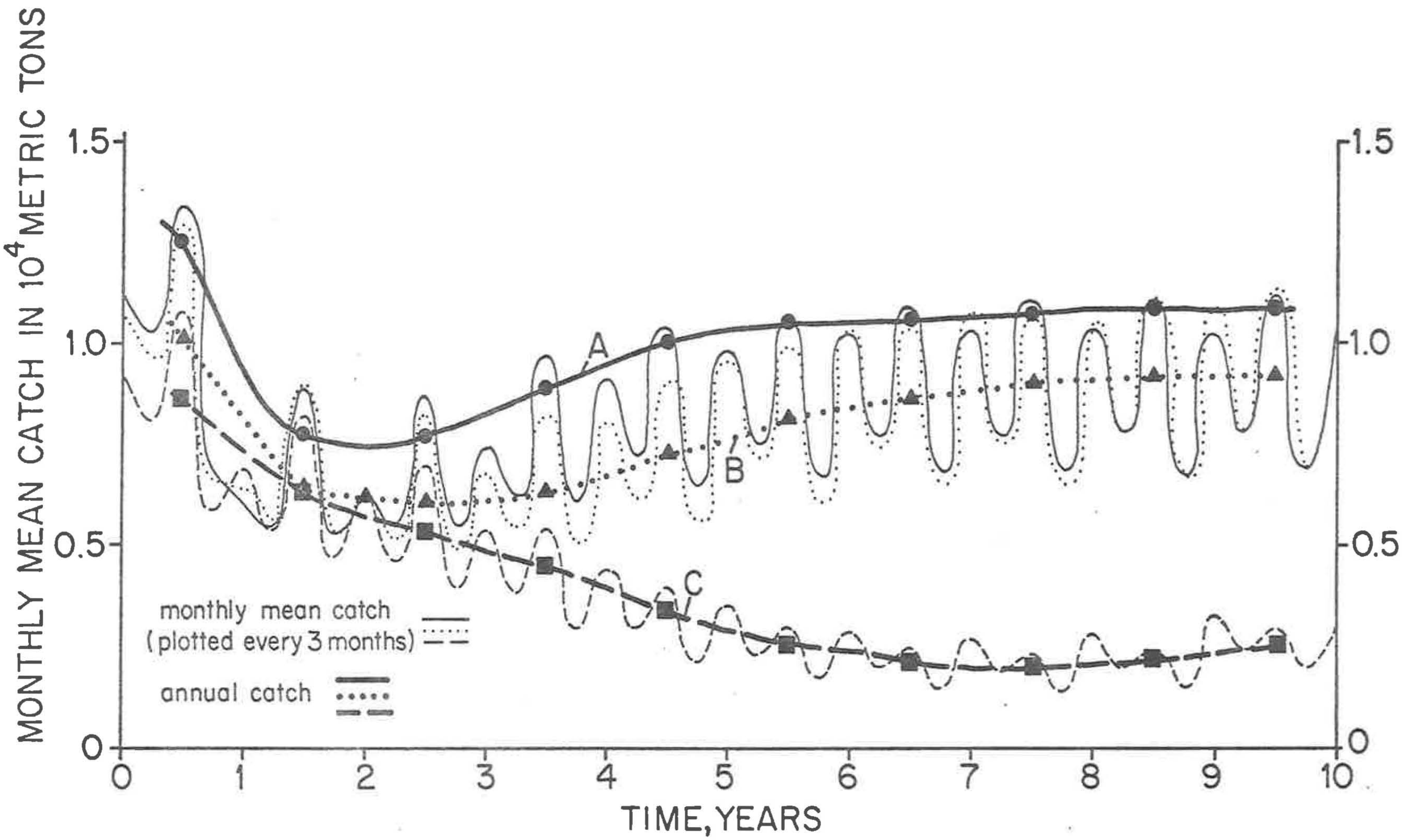


Figure 7.--Catch of pollock in eastern Bering Sea. A. present fishery; B. 80% of present fishing effort; C. 50% of present fishing effort.

long-period fluctuation with a period of about twelve years seems to be a "natural phenomenon" caused by internal ecosystem dynamics. However, this periodicity is affected by the fishery and probably by other factors, such as by environmental anomalies, as Figures 3 to 6 indicate. The fishery yield with 50% of present fishing effort decreases for seven and one-half years (Figure 7, curve C) and starts to increase thereafter. The pollock biomass changes using 80% of present fishing effort (curve B on Figures 3 to 7) behave analogously to the present fishing effort, except for differences in timing of decrease/increase.

In an earlier study with the present model, Laevastu, Dunn and Favorite (1976) showed that availability of food (copepods and specially euphausids) might be a limiting factor for the size of populations which depend on zooplankton for food. Furthermore, another recent study with the Bulk Biomass model for the eastern Bering Sea (Laevastu and Favorite, 1976) demonstrated that small pelagic fish (herring, capelin, smelt) are very heavily grazed and their availability is also apparently a limiting factor on the size of biomasses of fish (e.g., roundfish) grazing upon them. It will be shown in the next section that the cannibalism in pollock might be one of the causes of differing distributions of juvenile and adult pollock populations. Consequently two suggestions arise from the above results: first, many population sizes and their fluctuations might be caused by grazing intensities on larvae and juvenile populations and the effect of the size of spawning population on subsequent year class strength might be less than generally assumed in earlier population dynamics approaches; second, as the cod and sablefish in the Bering Sea occupy about the same ecological level and living space as pollock, the population sizes of these species might be controlled by pollock grazing upon juvenile cod and sablefish biomasses. When not in equilibrium, the biomasses of these two species (i.e., pollock and cod) might fluctuate in opposite rhythms.

Several recent studies show that food availability is a limiting factor in gonad development, as well as in reaching maturity, possibly *via* growth rate as affected by the spatially and temporally varying availability of food (e.g., Flüchter and Trommsdorf, 1966). Thus, two further hypotheses for further studies can be raised: first, that all sexually mature fish might not spawn each year (as known from empirical observations) due to a shortage of food in some areas and times; second, considering the results of the present study, described earlier, it might be postulated that a greater portion of adult pollock might mature earlier (and spawn at a younger age) in the case of intensive pollock fishery, as in this case a greater availability of food for medium size pollock can be expected (i.e., smaller older fish population and greater juvenile population, the latter presenting more and easier prey (cannibalism)). This hypothesis might be studied if sufficient field observations on age and maturity of pollock were available from the 1960's before the intensive pollock fishery.

IV. SPATIAL DISTRIBUTION OF POLLOCK IN THE EASTERN BERING SEA AS AFFECTED BY GRAZING AND FISHERY

The spatial distribution of juvenile and mature pollock in the eastern Bering Sea in February of the first year computations, (Figures 8 and 9), and the distributions of the same age groups of pollock after four years of computations using the present fishing effort (Figures 10 and 11) suggest a number of interesting relations. The center of the juvenile pollock distribution is, after four years, at the continental slope north of the Pribilof Islands (Figure 10), whereas the majority of adults are further offshore (Figure 11), with another, somewhat higher concentration over the central part of the continental shelf. This general distribution of pollock has been confirmed by 1975 eastern Bering Sea baseline studies (see NWAFC Proc. Rpt., 1976), although these results were not available at the time of the preparation of input to this model. The occurrence of juvenile pollock north of the Pribilof Islands has been well documented by Alton (1976). A similar distribution of older pollock with 50% of present fishing effort is shown (Figure 13), and the probable effect of grazing by mammals creating a lower concentration west of and around the Pribilof Islands, is more apparent. The abundance of juvenile pollock in February of the 5th year of computation using 50% of the present fishing effort (Figure 12) is now smaller that that computed for the same time step using the full fishing effort (see Figures 4 and 10), and its center has moved somewhat towards the southeast as compared to the same population with full present fishing effort. Furthermore, the areal extent of the population

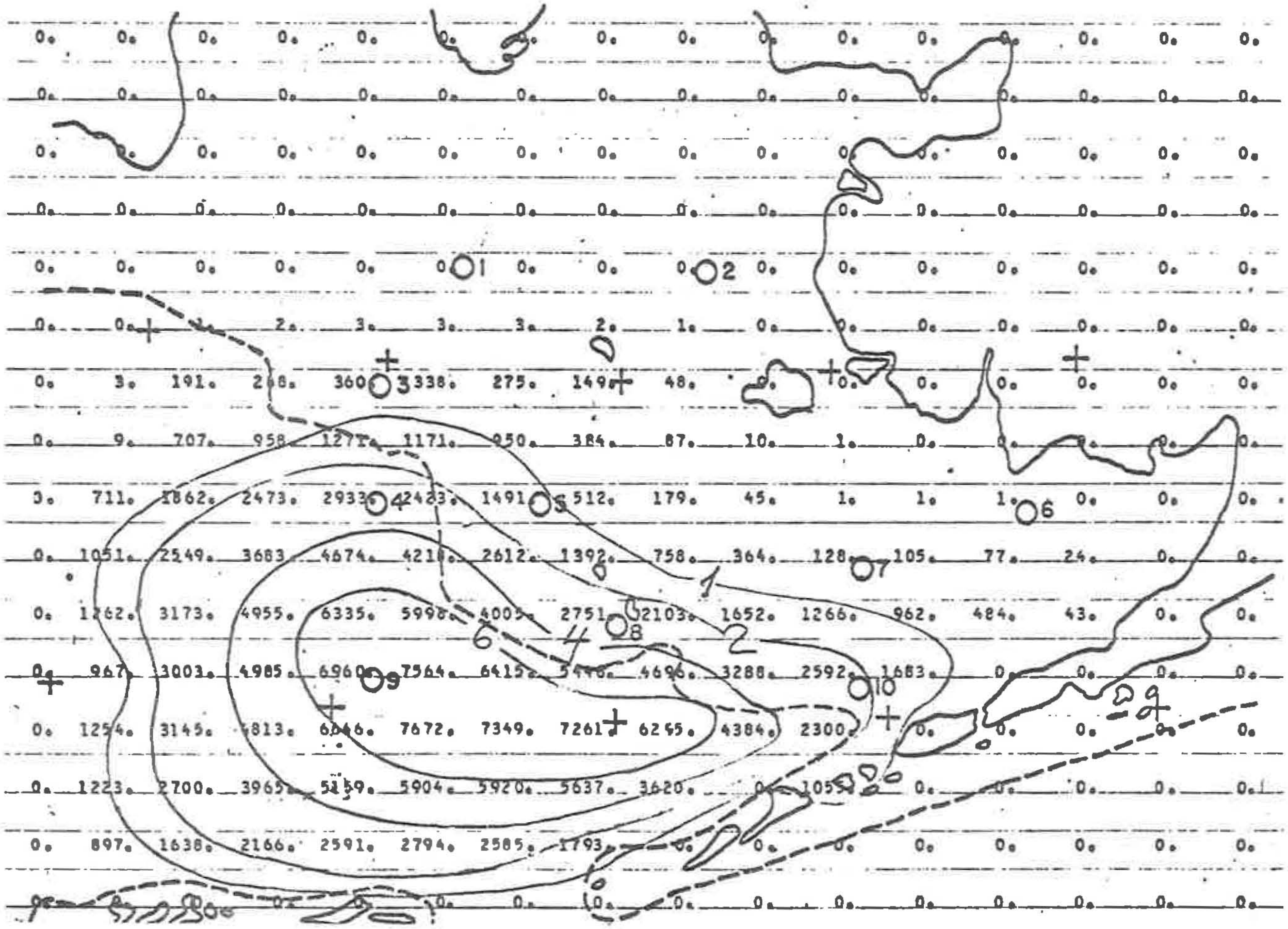


Fig. 8--Distribution of juvenile pollock in February, 1st year (present fishing effort) (tons/km^2).

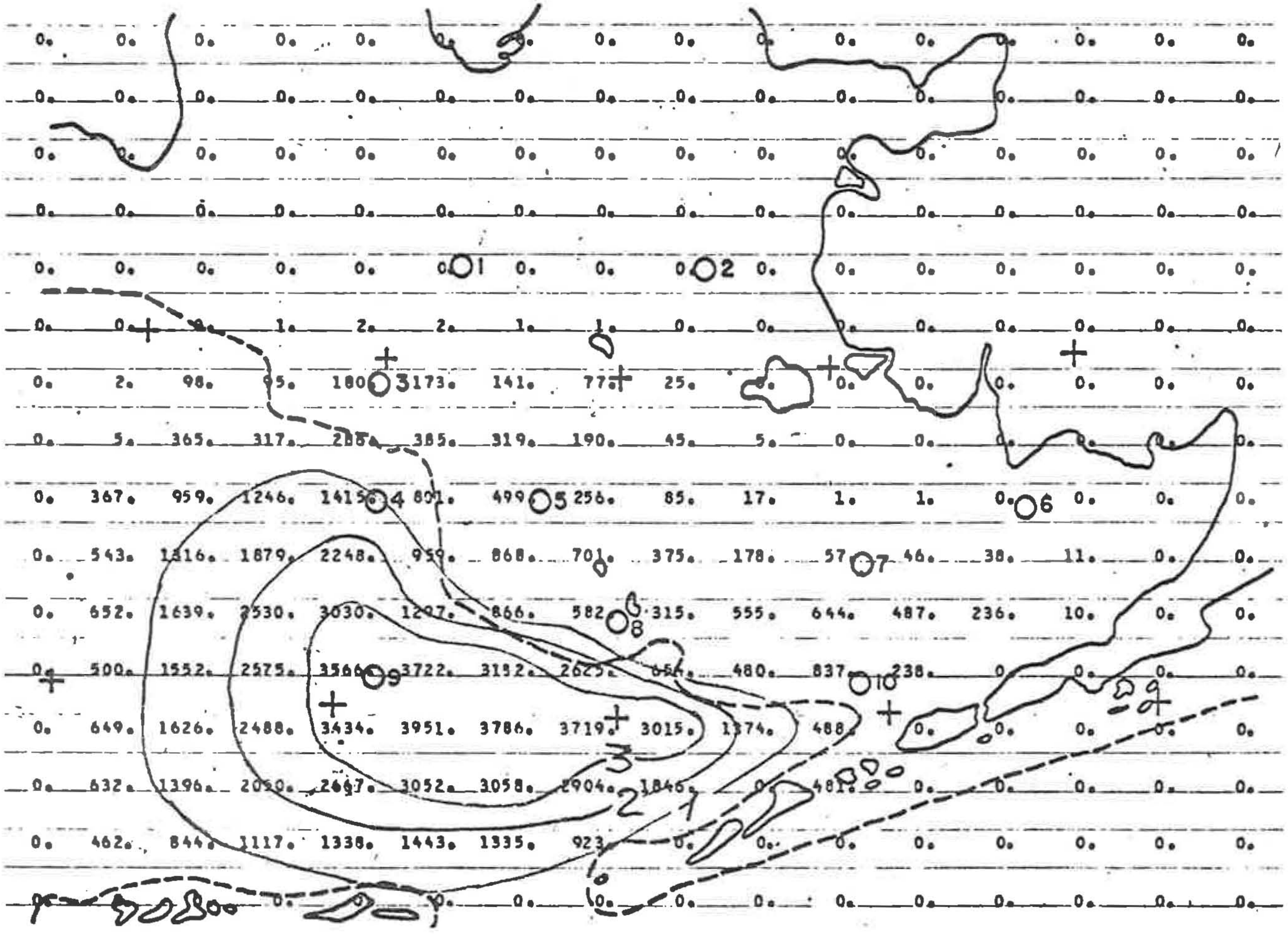
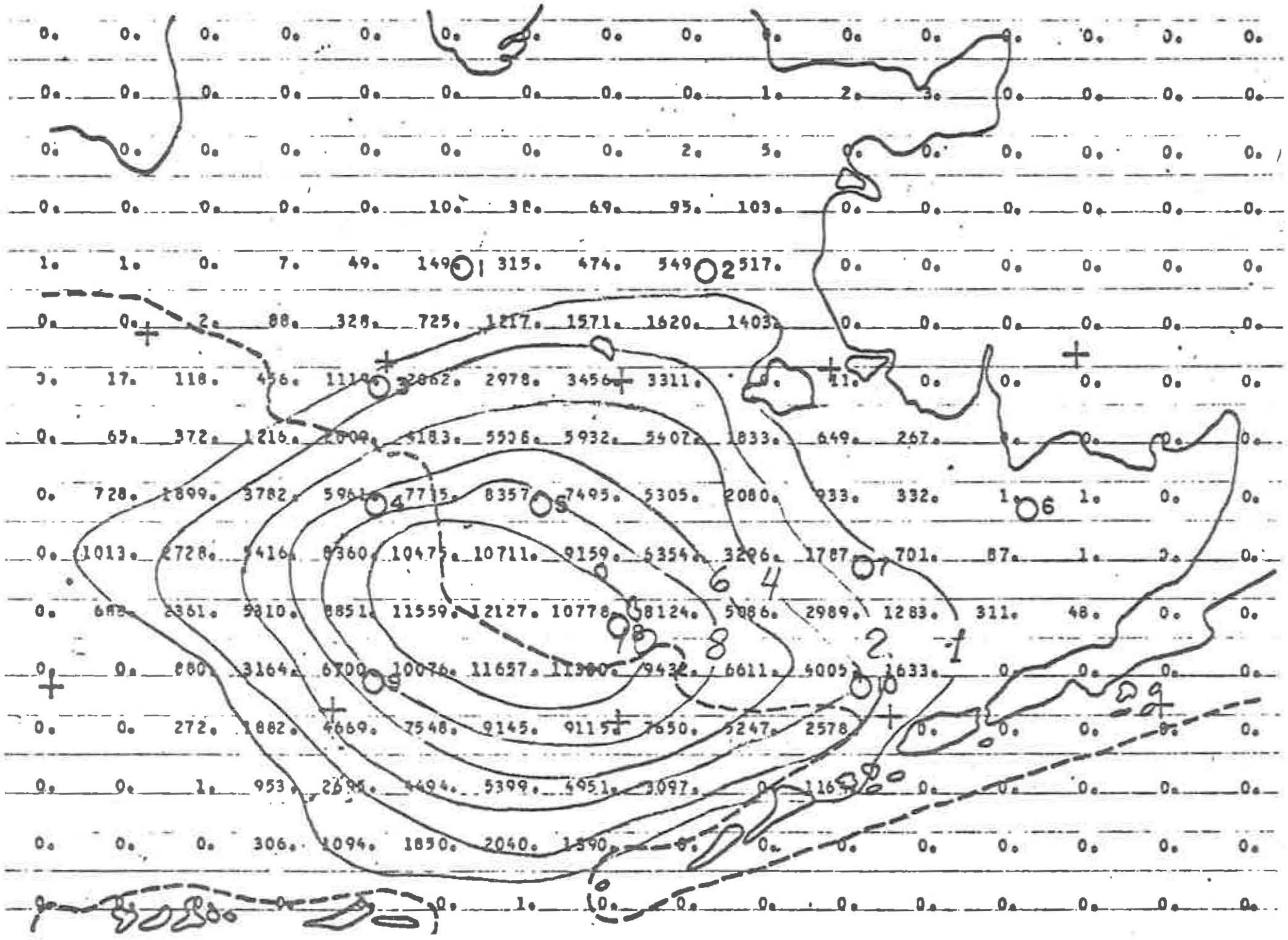


Fig. 9--Distribution of old (>45 cm) pollock in February, 1st year (present fishing effort) (tons/km^2).



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0.	1013.	2728.	5416.	8360.	10475.	10711.	9159.	6354.	3296.	1787.	701.	87.	1.	0.	0.
0.	683.	2361.	5810.	8851.	11559.	12127.	10778.	8124.	5086.	2989.	1283.	311.	48.	0.	0.
0.	0.	880.	3164.	6700.	10076.	11657.	11380.	9432.	6611.	4005.	1633.	0.	0.	0.	0.
0.	0.	272.	1882.	4669.	7548.	9145.	9115.	7650.	5247.	2578.	0.	0.	0.	0.	0.
0.	0.	1.	953.	2695.	4494.	5399.	4951.	3097.	0.	116.	0.	0.	0.	0.	0.
0.	0.	0.	306.	1094.	1850.	2040.	1390.	0.	0.	0.	0.	0.	0.	0.	0.
0.			0.		0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 10--Distribution of juvenile pollock in February, 5th year (present fishing effort) (tons/km^2).

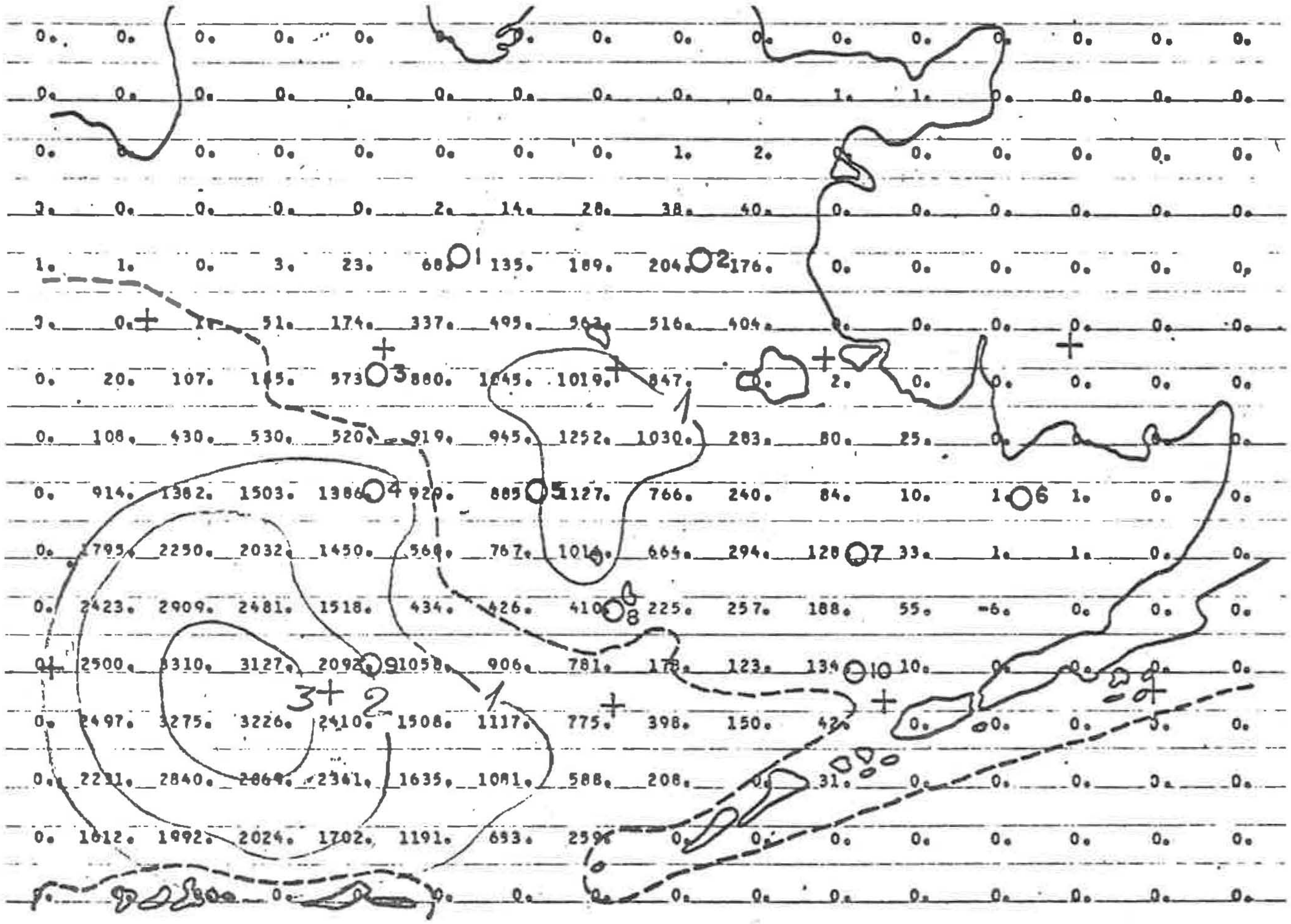


Fig. 11--Distribution of old (>45 cm) pollock in February, 5th year (present fishing effort) (tons/km^2).

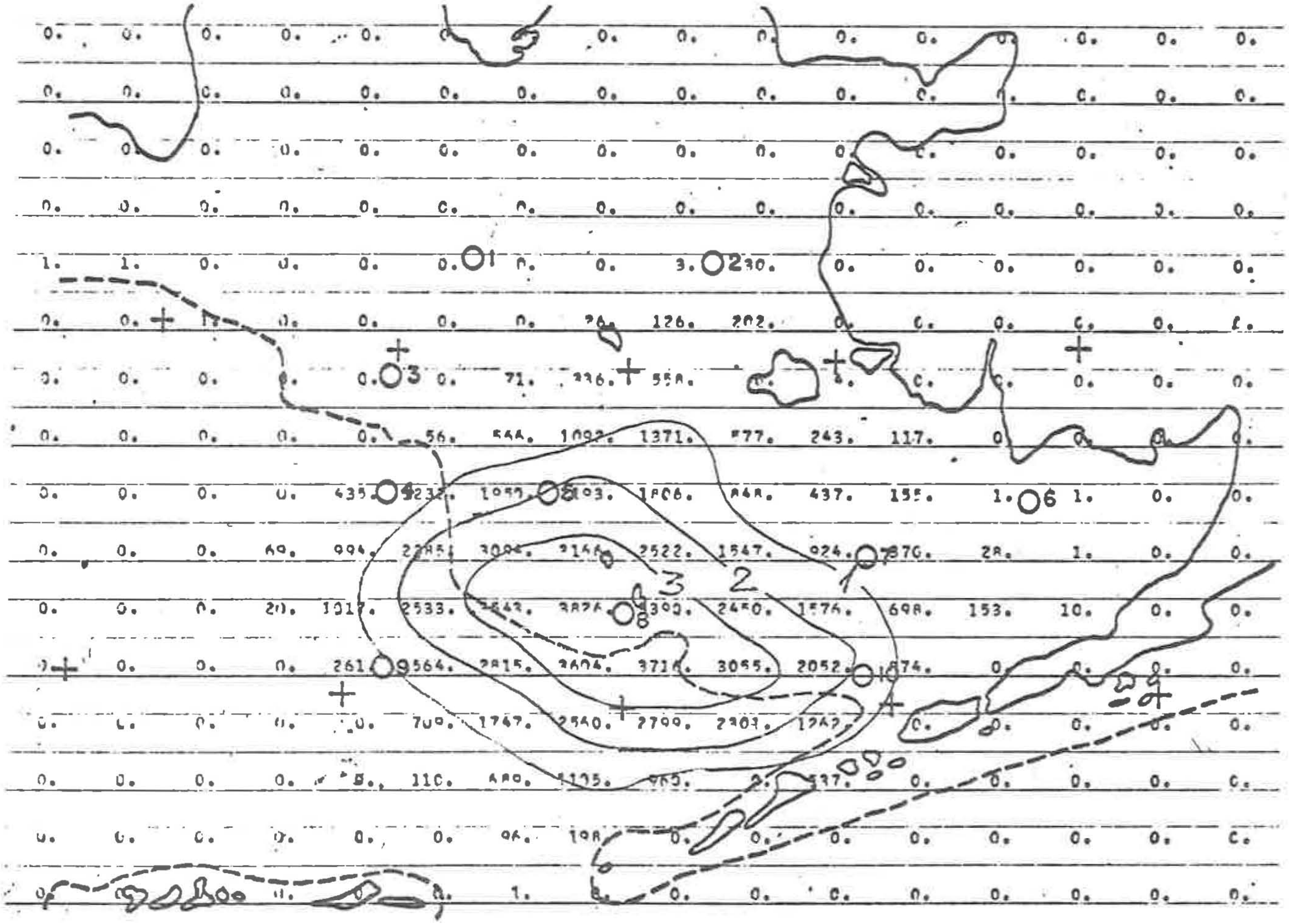


Fig. 12--Distribution of juvenile pollock in February, 5th year (50% of present fishing effort) (tons/km^2).

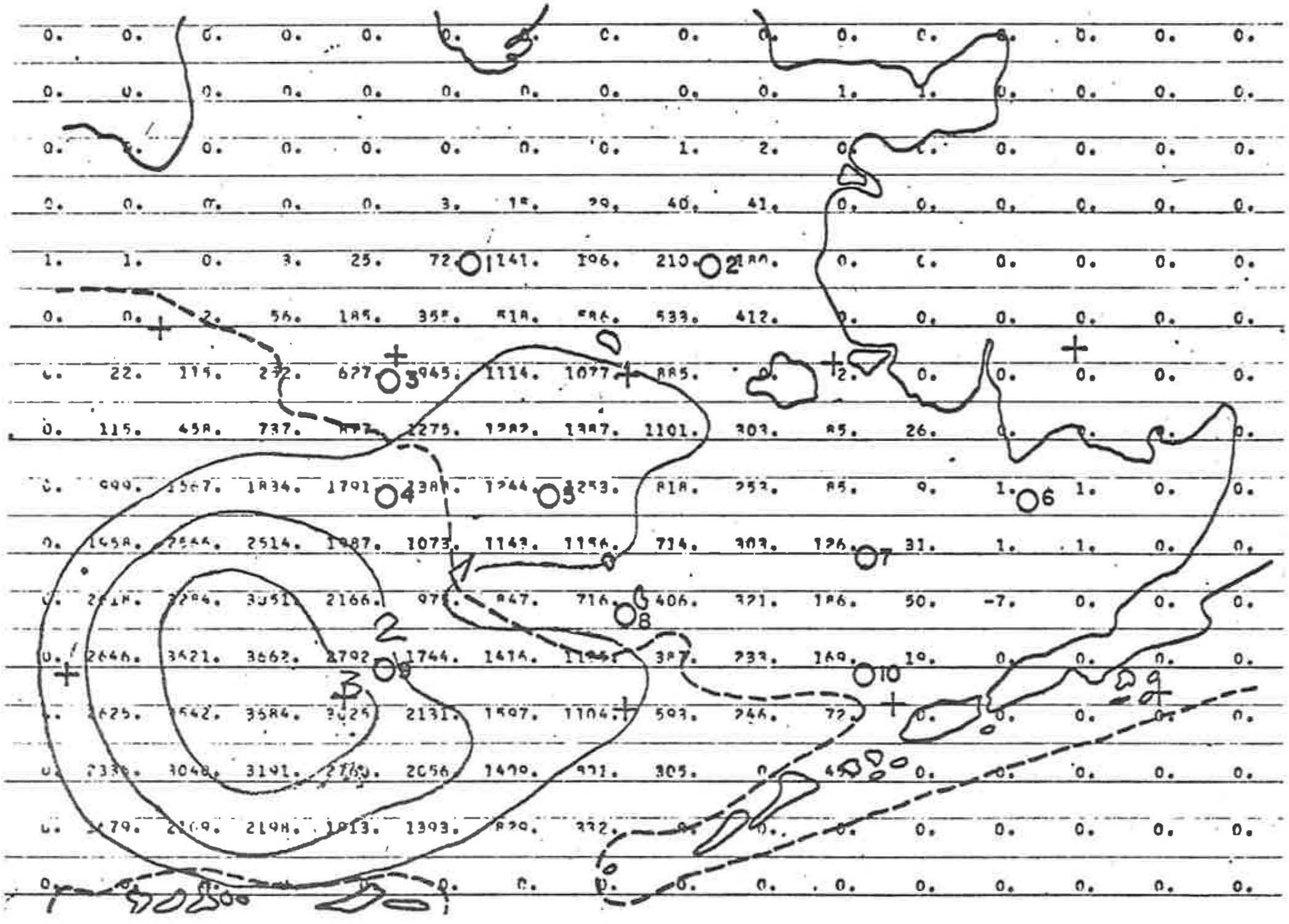


Fig. 13--Distribution of old (>45 cm) pollock in February, 5th year (50% of present fishing effort) (tons/km^2).

after about four years has shrunk considerably. The shrinking of declining populations towards their centers of main abundance and the first disappearance of "fringe populations" with a dereasing population seems to be a rather common phenomenon, indicated by the model. On the other hand, the model indicates that an increasing populations spreads, an intuitively reasonable occurrence at least to the extent that food and physical environment are not limiting and for which actual examples are available. The latter is partly a mathematical artifact from a Laplacian smoothing operator, but also partly a real consequence of population growth. There have been some observations that pollock have become more abundant in the northern Gulf of Alaska in recent years, which might partly be a consequence of the recent apparent increase of juvenile pollock population in the Bering Sea, as predicted by our model. However, other local factors might determine the fluctuations of pollock population in the Gulf of Alaska, which will be studied with the DYNUMES model when adapted to this area in the future.

The partial separation of juvenile and adult pollock populations already occurs during the summer of the first year's computation (see Figures 14 and 15), whereas on the continental shelf the remaining population has two higher concentrations, one south of the Pribilof Islands, and one about 60°North. After four years of computation with present fishing effort, the separation of juvenile and adult populations is more complete (Figures 16 and 17) despite the fact that both populations are advanced with the same annual migration speed in the model. The distribution of the adult population with 50% of the present fishing effort is about the same as with full fishing effort (Figure 19), but the juvenile population has shrunk somewhat (Figure 18).

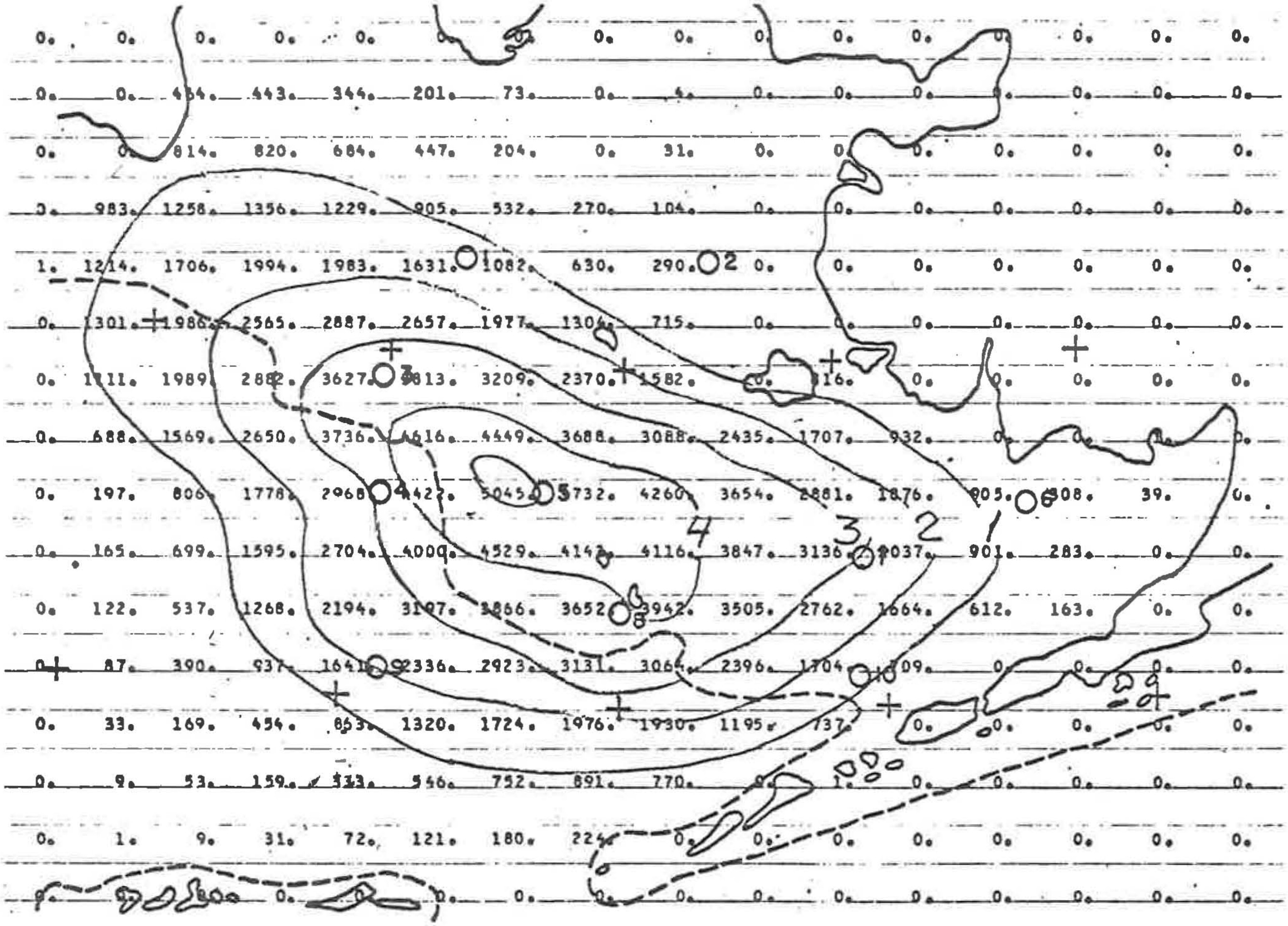
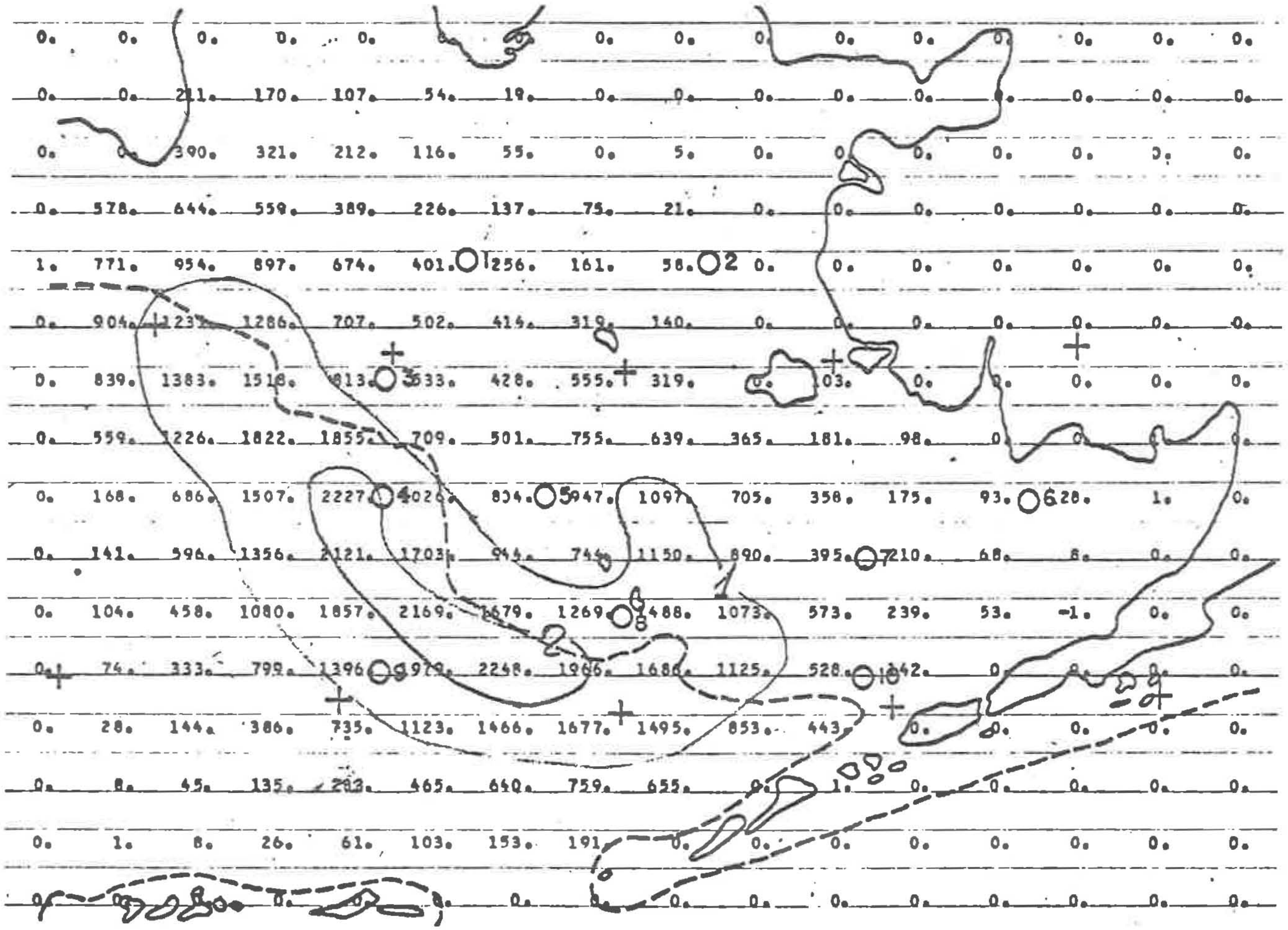
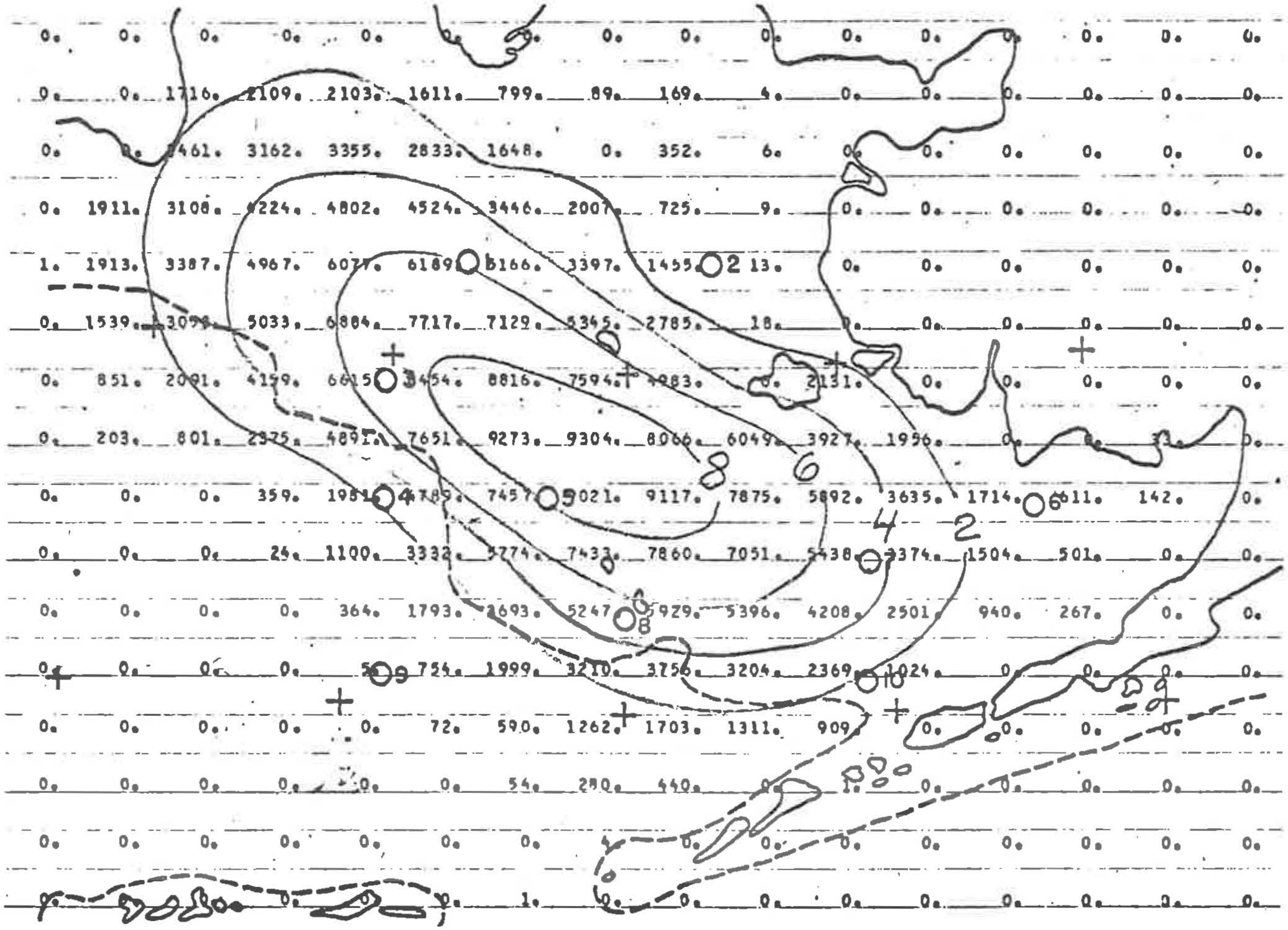


Fig. 14--Distribution of juvenile pollock in August, 1st year, (present fishing effort) (tons/km^2).



0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	211.	170.	107.	54.	19.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	390.	321.	212.	116.	55.	0.	5.	0.	0.	0.	0.	0.	0.	0.
0.	578.	644.	559.	389.	226.	137.	75.	21.	0.	0.	0.	0.	0.	0.	0.
1.	771.	954.	897.	674.	401.	256.	161.	58.	0.	0.	0.	0.	0.	0.	0.
0.	904.	1237.	1286.	707.	502.	414.	319.	140.	0.	0.	0.	0.	0.	0.	0.
0.	839.	1383.	1518.	1813.	533.	428.	555.	319.	0.	103.	0.	0.	0.	0.	0.
0.	559.	1226.	1822.	1855.	709.	501.	755.	639.	365.	181.	98.	0.	0.	0.	0.
0.	168.	686.	1507.	2227.	[illegible]	834.	947.	1097.	705.	358.	175.	93.	28.	1.	0.
0.	141.	596.	1356.	2121.	1703.	944.	744.	1150.	890.	395.	210.	68.	8.	0.	0.
0.	104.	458.	1080.	1857.	2169.	1679.	1269.	1488.	1073.	573.	239.	53.	-1.	0.	0.
0.	74.	333.	799.	1396.	[illegible]	2248.	1966.	1686.	1125.	528.	142.	0.	0.	0.	0.
0.	28.	144.	386.	735.	1123.	1466.	1677.	1495.	853.	443.	0.	0.	0.	0.	0.
0.	8.	45.	135.	283.	465.	640.	759.	655.	0.	1.	0.	0.	0.	0.	0.
0.	1.	8.	26.	61.	103.	153.	191.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 15--Distribution of old (>45 cm) pollock in August, 1st year (present fishing effort) (tons/km^2).



0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	1716.	2109.	2103.	1611.	799.	89.	169.	4.	0.	0.	0.	0.	0.	0.
0.	0.	1461.	3162.	3355.	2833.	1648.	0.	352.	6.	0.	0.	0.	0.	0.	0.
0.	1911.	3108.	4224.	4802.	4524.	3446.	2007.	725.	9.	0.	0.	0.	0.	0.	0.
1.	1913.	3387.	4967.	6077.	6189.	6166.	3397.	1455.	13.	0.	0.	0.	0.	0.	0.
0.	1539.	3098.	5033.	6884.	7717.	7129.	5345.	2785.	18.	0.	0.	0.	0.	0.	0.
0.	851.	2091.	4159.	6615.	3454.	8816.	7594.	4983.	0.	2131.	0.	0.	0.	0.	0.
0.	203.	801.	2375.	4891.	7651.	9273.	9304.	8066.	6049.	3927.	1956.	0.	0.	33.	0.
0.	0.	0.	359.	1951.	4789.	7457.	9021.	9117.	7875.	5892.	3635.	1714.	611.	142.	0.
0.	0.	0.	24.	1100.	3332.	5774.	7433.	7860.	7051.	5438.	3374.	1504.	501.	0.	0.
0.	0.	0.	0.	364.	1793.	2693.	5247.	5929.	5396.	4208.	2501.	940.	267.	0.	0.
0.	0.	0.	0.	[illegible]	754.	1999.	3210.	3756.	3204.	2369.	1024.	0.	0.	0.	0.
0.	0.	0.	0.	0.	72.	590.	1262.	1703.	1311.	909.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	54.	280.	440.	0.	1.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.		0.	0.	0.	0.	0.	0.	0.	0.
0.			0.		0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 16--Distribution of juvenile pollock in August, 5th year (present fishing effort) (tons/km^2).

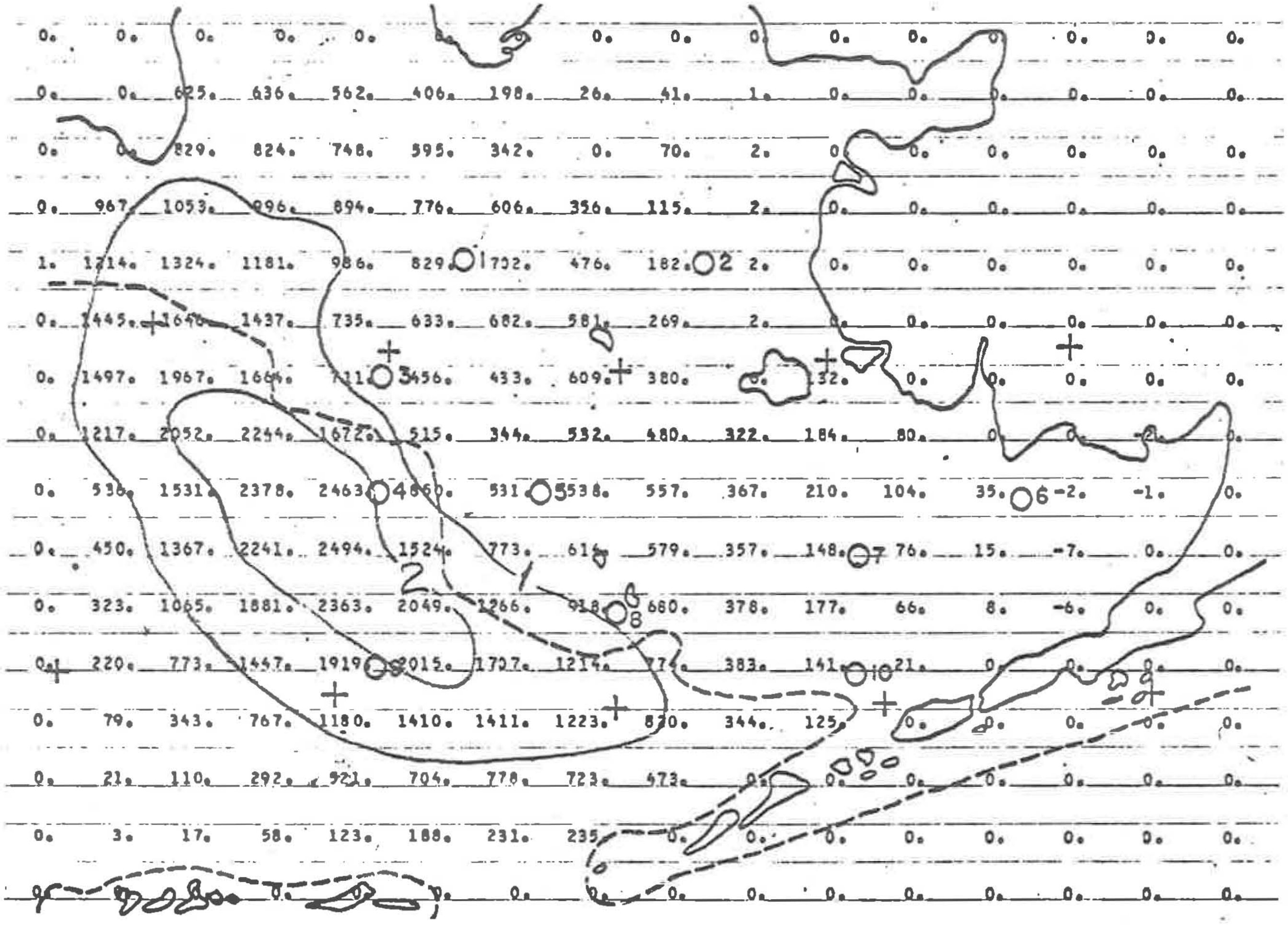


Fig. 17--Distribution of old (>45 cm) pollock in August, 5th year (present fishing effort) (tons/km^2).

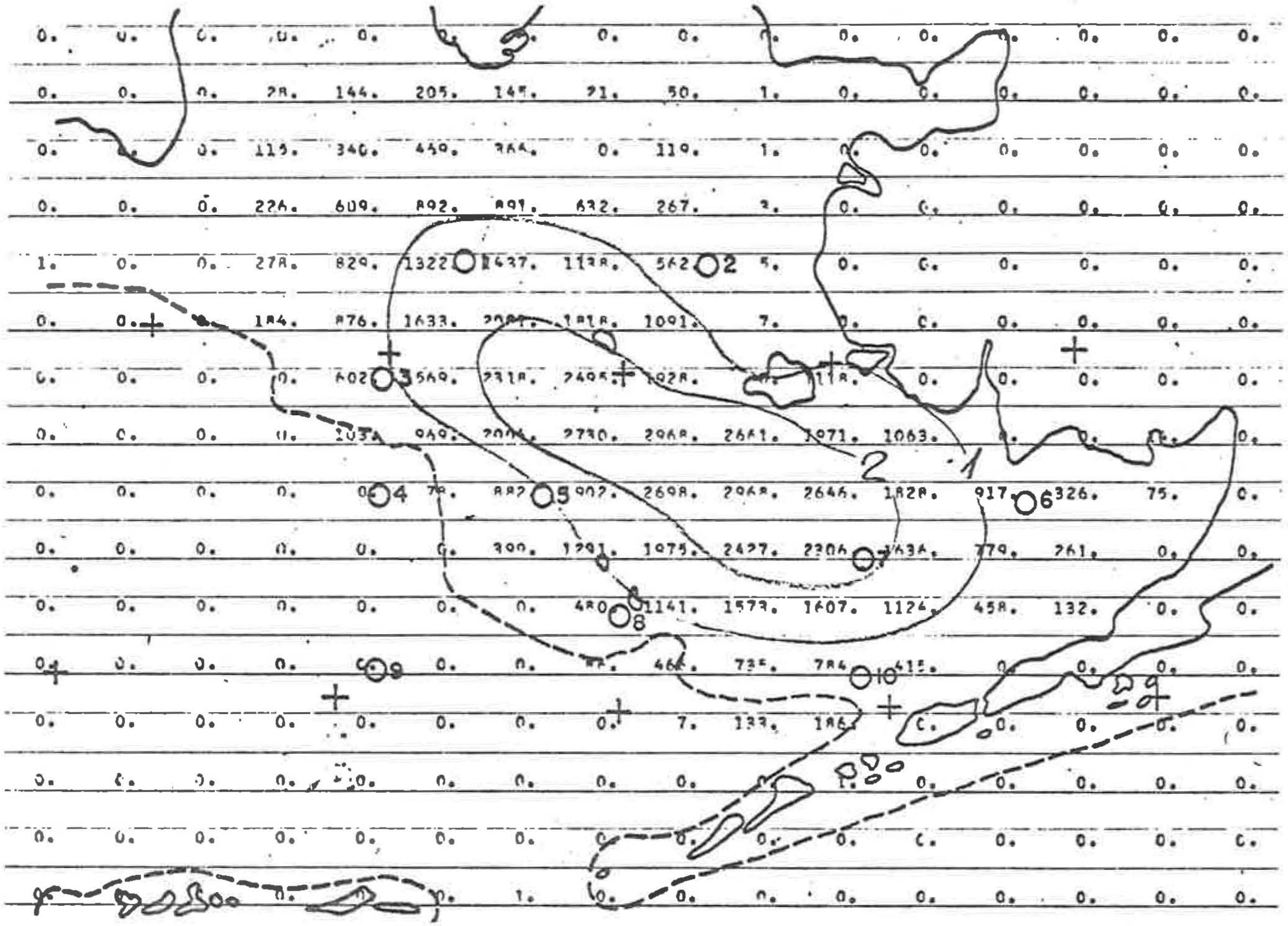


Fig. 18--Distribution of juvenile pollock in August, 5th year (50% of present fishing effort) (tons/km^2).

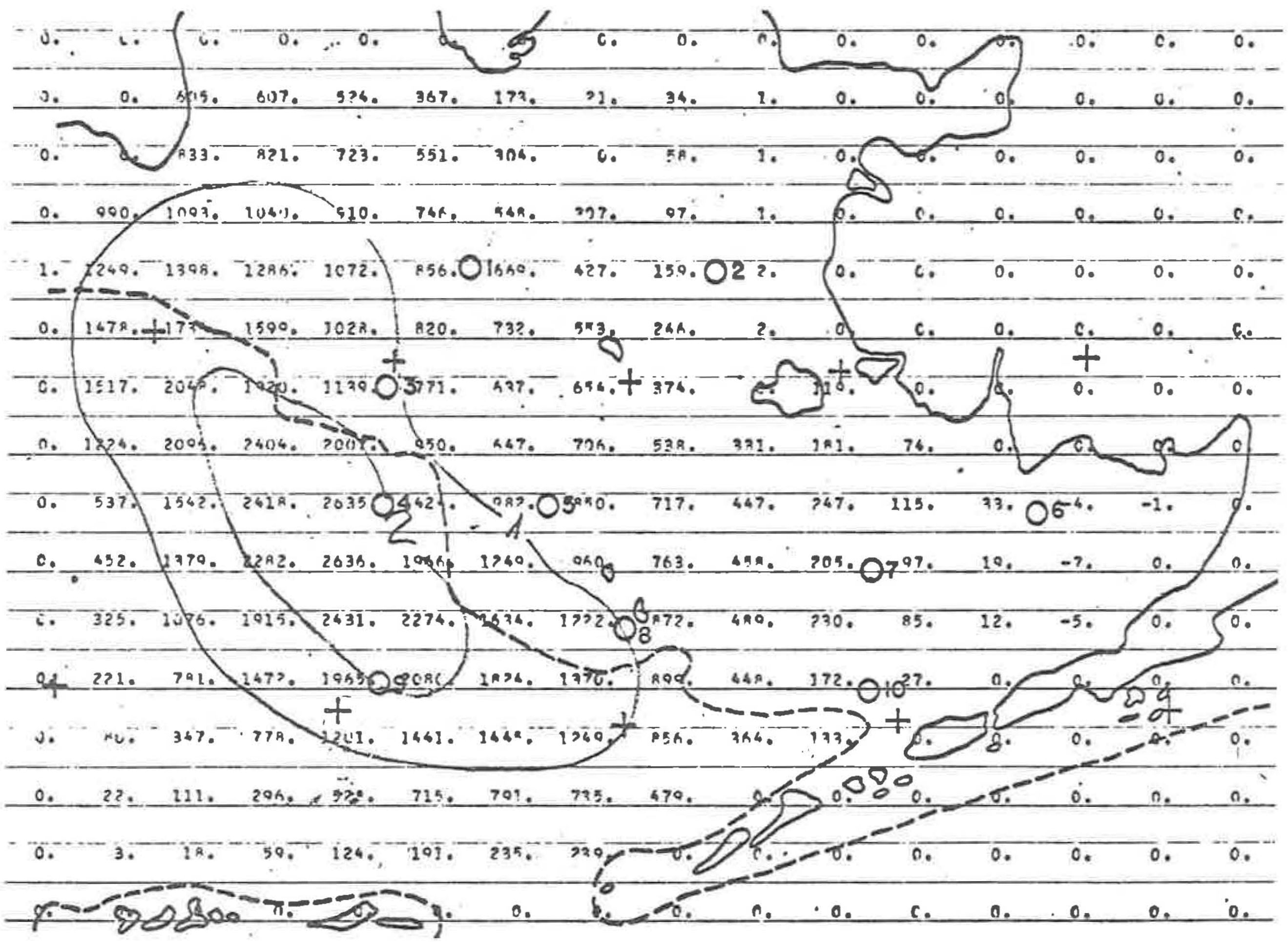


Fig. 19--Distribution of old (>45 cm) pollock in August, 5th year (50% of present fishing effort) (tons/km^2).

V. INTERACTIONS BETWEEN HERRING AND POLLOCK POPULATIONS

The model was run with two herring biomasses; one, which was slightly below the minimum sustainable biomass (i.e., 1 million tons), and the other somewhat above it (*ca* 1.5 million tons), (see Figure 20). The changes in both herring biomasses with time and with different fishing effort on pollock (but constant fishing effort on herring) during the first two years of computation (Figure 20) indicate that the herring biomass remains higher using the present (higher) fishing effort on pollock (curves marked A) than with the lower (50% of present) fishing effort on pollock (curves marked C). The cause of this difference is the increased grazing by older age pollock on herring, as the biomass of the older pollock group is higher during the first five years (see Figure 6, curve C) with lower fishing effort.

Assuming a high initial herring population, this population increases with time, until food availability becomes limiting. However, a lower than "minimum sustainable" biomass (lower curves on Figure 20) continues to decline due to ecosystem internal grazing.

The areal distribution of herring in December of the first year of computation, (Figure 21) and the distribution of herring in January of the fifth year (with declining population, initial population 1 million tons) with present fishing intensity and 50% of present fishing intensity on pollock respectively (Figures 22 and 23), indicate different distributions which are caused by different grazing pollock populations. The last distribution (Figure 23) shows the herring distributions shrinking to two centers, one south of the Pribilof Islands and the other at about 60^{O}North. The area near the continental shelf north of Pribilof Islands

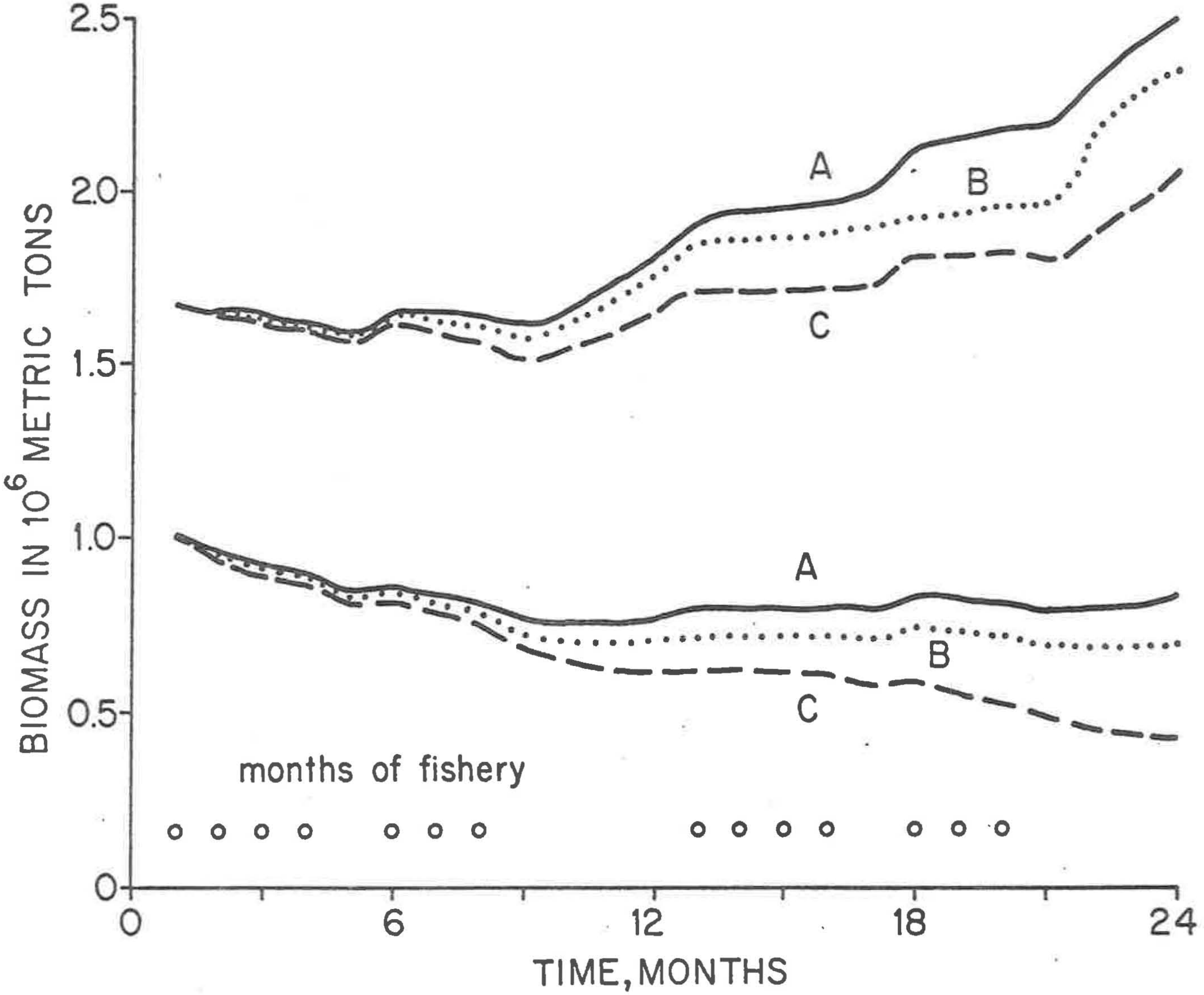


Figure 20.--Changes of "herring" biomass in eastern Bering Sea. A. present fishery on pollock; B. 80% of present fishing effort on pollock; C. 50% of present fishing effort on pollock.

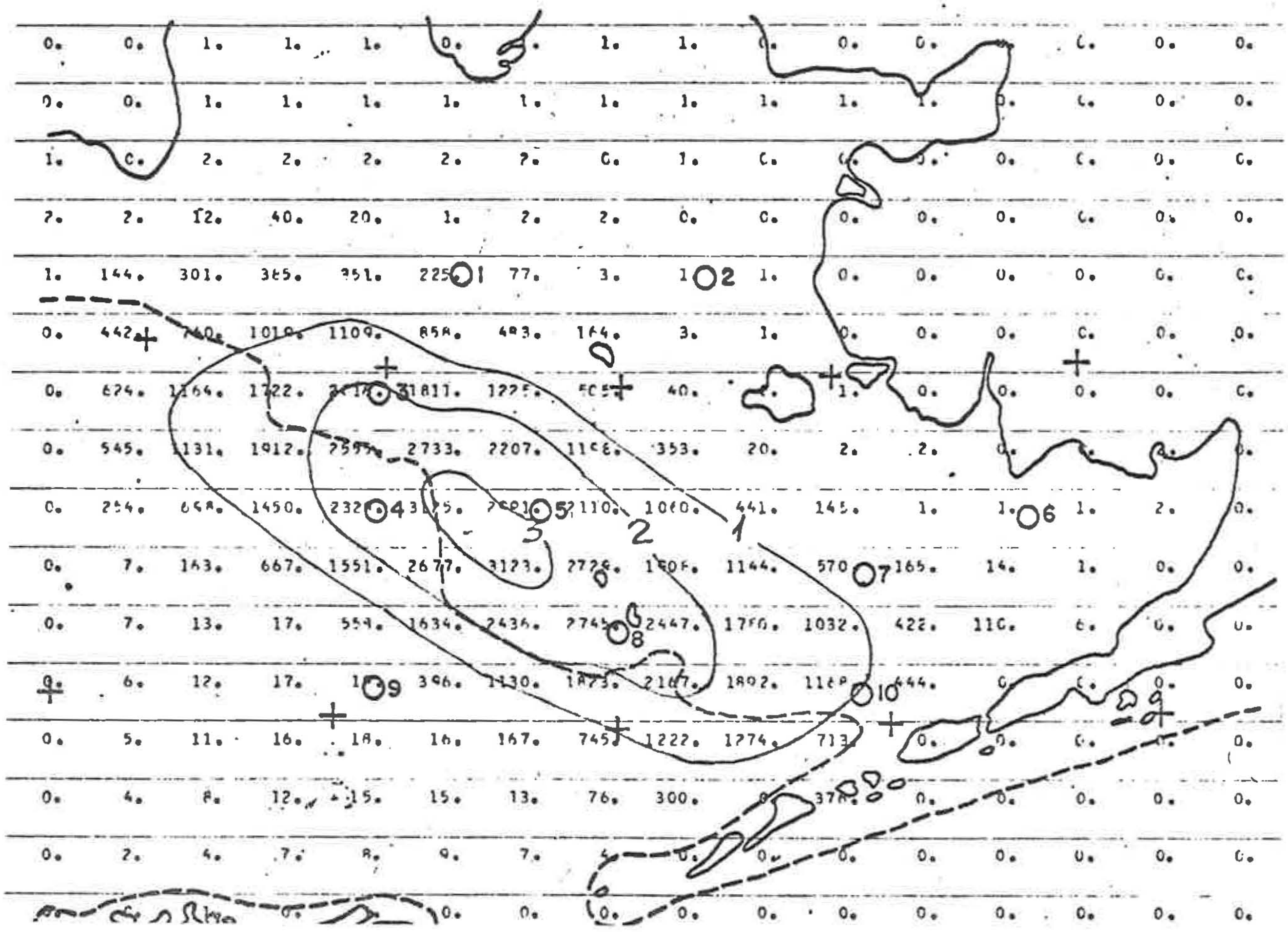


Fig. 21--Herring distribution in December, 1st year (present fishing effort on pollock, initial biomass 1 million tons) (tons/km^2).

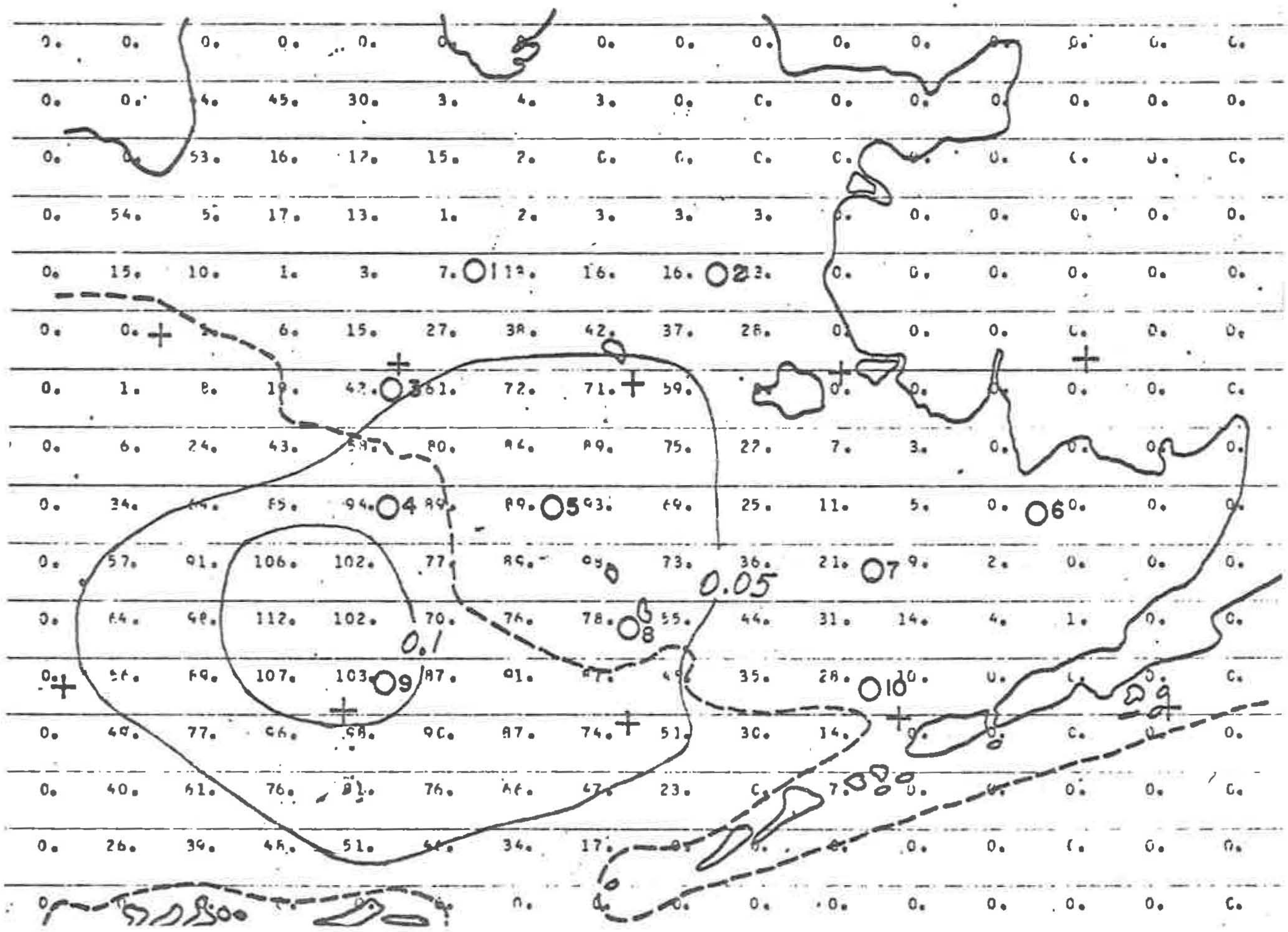


Fig. 22--Herring distribution in January, 5th year (present fishing effort on pollock, initial biomass 1 million tons) (tons/km^2).

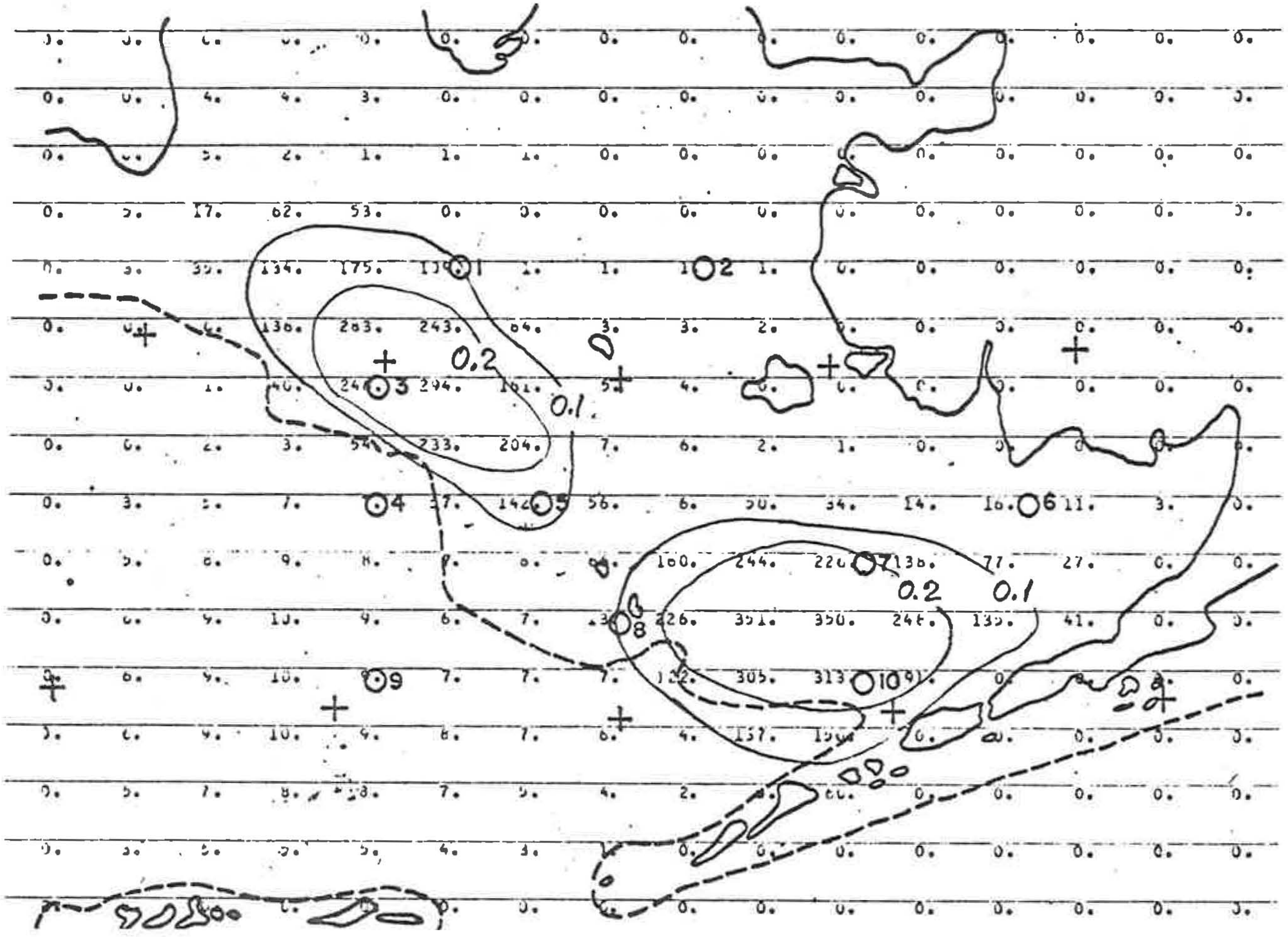


Fig. 23--Herring distribution in January, 5th year, 50% of present fishing effort on pollock (initial biomass 1 million tons)(tons/km^2).

is nearly void of herring according to this computational result. This, and other indications from model results, suggest that the near disappearance of shrimp stock north of the Pribilof Islands might have been caused partly by grazing by pollock, after the pollock had grazed down the local herring population, even though Bakkala, Kessler and MacIntoch (1976) suggest environmental changes as a probable cause. These shrimp stocks were also very heavily exploited by Japan, (catches of about 30 K mt in 1963 to only a trace by 1968). It is difficult to observe the fluctuations in abundance of herring in the eastern Bering Sea from catch data, as the catch of this species is very small in relation to the population size (ca 5% removed annually by fishery).

Finally, it should be emphasized that the primary use of model studies is to raise suggestions for research, indicate priorities, and provide verification and testing of hypotheses which find applications either in science or in practice. The numerous tentative conclusions presented in this paper should be treated as suggestions, unless supported by empirical evidence and/or verified by further research.

VI. SUMMARY

An 8-component submodel of the DYNUMES model was used to investigate some aspects of pollock and herring biomass dynamics in the eastern Bering Sea that cannot be studied with single-species population dynamics models. The initial January distribution of both fish stocks was prescribed. Thereafter, the biomasses were moved numerically around in the Bering Sea in conformance to known seasonal migrations. The growth, grazing, and fishery loss was computed in monthly time steps for 10 years. Model runs using the present exploitation level, as well as decreased fishing intensities, were computed for the study of the effects of fishery on these two species biomasses. The following tentative conclusions were reached:

1. Because older pollock consume juveniles (cannibalism), the dynamics of the pollock population depends greatly on the size of the older pollock biomass, which, if large, can suppress the juvenile biomass by grazing.

2. The interactions between the cannibalism and the different growth rates of different age groups of the biomass can cause long-term fluctuations in the pollock biomass. The present results indicate that the period of this long-term fluctuation is about 12 years and that the fishery can affect this periodicity.

3. The present intense fishery on pollock removes part of the older, cannibalistic part of the biomass and decreases therewith grazing pressure on the faster growing juvenile biomass, thus causing an increase in biological production (growth) of total pollock biomass

in the eastern Bering Sea. With present fishing effort (intensity) the "minimum sustainable" (defined in text) biomass of pollock decreases in the first year to slightly above 4 million tons and increases thereafter, reaching 5.7 million tons after 4 years. Subsequently the limitation of growth of the juvenile biomass (programmed in the model to limit the growth of juvenile biomass when this becomes large and would be limited by the availability of food) becomes effective.

4. With a lower than present fishing effort on pollock, the older fish biomass increases relative to the juvenile and medium-age pollock biomass, but total pollock biomass decreases. With 50% lower fishing effort from present, the total pollock biomass decreases for 6 years, reaching a level slightly below 2 million tons before it starts to increase again. The details of the fluctuation of intensively fished and slightly fished pollock populations changes with time are as follows:

a. The size change of total pollock population is dependent on the size of the juvenile population from which the older groups recruit their growth. The juvenile population is affected by grazing by other ecological groups (mammals, birds, sablefish, etc.) as well as by cannibalism within the pollock population. On the other hand, cannibalism is a function of the size of the older age group pollock population which obtains more than 50% of its food requirements by feeding on juvenile pollock (see Figure 2).

b. If intense fishing is conducted (ca 1.25 million tons a year, approximately the present fishery) the oldest pollock are removed rapidly (within about one year) and the medium-sized (25 to 45 cm) pollock population is decreased by fishery within the first 3 years. The juvenile (pre-fishery) population starts to increase after 1 year and reaches its highest level in 4 years (food availability as a population limiting factor comes into effect thereafter). This juvenile population increase is principally due to faster growing rates of juveniles (see Table 3) and decreased grazing pressure (cannibalism) by lowering the biomass of older fish by the fishery. Due to higher level recruitment from the increasing juvenile (pre-fishery) stock, the medium and older stock also increase slightly after the third year; the medium-sized stock reaching a quasi-equilibrium state in 4½ years and the older in 6 years.

c. If less intense fishing is conducted (50% of present fishing effort), the initially prescribed juvenile population decreases for 5½ years, after which it starts to increase again suggesting a long period fluctuation. This decrease is due to the presence of older (longer than 45 cm) pollock that are assumed to be highly cannibalistic (see Table 1) on juveniles. The population of the older fish increases the first 3 years and starts to decrease thereafter due to decreased recruitment from juveniles (and from previous year classes, i.e., medium-sized pollock). The medium-sized pollock (25 to 45 cm) decreases for 6½ years, after which it starts to increase slightly. This decrease/increase is due to corresponding changes in abundances of juveniles from which the recruitments come to this group, thus, the changing size (age) composition reflects the state of the pollock stock and can be used as a predictor of its future dynamics.

d. With constant present fishing effort, landings are decreased during the first year due to removal of older (larger) fish (in our model from 1.25 million tons to .78 million tons in second and third year). Thereafter, the yield increases (to about 1 million ton) remaining relatively steady thereafter. The quasi-steady state is caused by assumption in the model that there is a limit to the size of juvenile population (food availability and grazing as limiting factors).

e. Decreasing the present fishing intensity by 50%, the catches decreased steadily from 0.75 to 0.25 million tons in the sixth year and remained quasi-steady thereafter. Decreasing the present fishing intensity by only 20% the catches decreased in the second year to about 0.75 million tons and started to increase in the third year, reaching a level of *ca* 0.9 million tons in the seventh year.

5. The numerical ecosystem submodel indicates that in addition to grazing, the availability of food seems to be a limiting factor for younger, large populations of pollock. The grazing and competition for food might be a plausible explanation why cod and sablefish populations are only a fraction of the pollock population, although these species are on the same ecological level as the pollock. It might be possible that due to ecosystem internal competition for food and grazing on each others juveniles, the pollock population on the one hand and cod and sablefish populations on the other hand, fluctuate in opposite rhythm. This will be investigated in future models in which these species will also be included.

6. As several recent tank tests show that food is a limiting factor in gonad development (e.g., Flüchter and Trommsdorf, 1974), as well as in reaching maturity, (via growth rate as affected by availability of food), it might be postulated that a greater proportion of adults mature earlier in the case of intensive pollock fishery (influenced by greater availability of food for medium-sized pollock via cannibalism) than in cases of no or little fishery. This might be studied (verified) by available data .

7. Heavy grazing by mammals (fur seal and sea lion) that removes at least as much pollock as the present fishery, causes an apparent bipartition in distribution of older pollock populations. This distribution gives an appearance of two separate populations in the Bering Sea where possibly only one exists. The bulk of the juveniles, however, is located during summer in the areas of lower concentration of older adults, thus decreasing the possibility of cannibalistic grazing.

8. The shifts in abundance of various age groups of pollock can cause changes in grazing pressure on herring and thus cause fluctuations in herring abundance. The fringe populations of herring seem to be grazed first and the population shrinks, according to the model results, towards the center of its abundance.

9. The "shrinking" of juvenile pollock population towards its mass center is also shown by the model. This shrinking occurs when juvenile population is low in relation to adult population. On the other hand, spreading of juveniles occurs when population is high. This might partly explain the observed greater abundance of pollock in the Gulf of Alaska in recent years. However, the Gulf of Alaska pollock population might be controlled by local factors, which will be investigated with another DYNUMES model in the future.

10. With high fishing intensity on pollock, the herring population increased in the model. The increase was less with lower fishing intensity on pollock, and there was a decrease in herring population in the absence of a pollock fishery, although the latter result is not shown on the figures. This change in the herring population in the model is caused by ecosystem internal grazing. If a lower initial herring population is selected, it decreases, but decreases slower with an intensive fishery on pollock than with less intensive pollock fishery. Thus, an intensive pollock fishery seems to be beneficial to the herring population according to our present model.

11. There are other small pelagic fish besides herring (capelin and smelt) in the Bering Sea which serve as a food source for pollock. Their abundance and distribution is at present little known. It can be postulated that as shrimp is also an important food item for medium and large sized pollock, its disappearance north of the Pribilof Islands in the late 1960's might have been influenced by the recent increase of the pollock population (increased grazing) brought about by the increased fishery in the mid-1960's.

The above are interim conclusions which might be modified in continued research and improvement of the model. The quantitative results are expected to change slightly when better food coefficients and time/space varying food composition of the species can be introduced into the improved model. However, most of the trends and qualitative results indicated above are expected to remain unchanged.

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