NOAA Technical Memorandum NMFS F/NWC-50

A Numerical Simulation Model of the Population Dynamics of Walleye Pollock, *Theragra chalcogramma* (Pallas 1811), in a Simplified Ecosystem:

Part II, Model Calibration, Validation, and Exercise

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October 1983

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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A NUMERICAL SIMULATION MODEL OF THE POPULATION DYNAMICS OF WALLEYE POLLOCK, *THERAGRA CHALCOGRAMMA* (PALLAS 1811), IN A SIMPLIFIED ECOSYSTEM: PART II, MODEL CALIBRATION, VALIDATION, AND EXERCISE

by

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ABSTRACT

This report describes model calibration, validation, and results of simulation exercises using an age-structured energetics and population model of walleye pollock, Theragra chalcogramma (Pallas 1811), in a simplified Bering Sea ecosystem consisting of phytoplankton, copepods, and euphausiids. The model was described in detail in Knechtel and Bledsoe (1981).

Calibration was accomplished primarily by manual variation of parameters until a subjective set of target criteria for realism of plankton biomasses and pollock numbers, lengths, weights, and fishery catches were adequately met.

For validation, the principal variables describing the state of the model system were compared with actual data concerning the Bering Sea walleye pollock population and the surrounding ecosystem. Statistically significant similarities and differences were found, indicating that the model provides useful insights and predictions, but further model improvements may be possible.

Exercises indicated that the simulated walleye pollock population was capable of recovery from severe overfishing, that walleye pollock in the present fishery are limited by food supply, and that the population under present conditions may tend toward a constant equilibrium. Simulated walleye pollock population dynamics showed equilibrium, periodic, or pseudorandom (chaotic) behavior. The type of behavior which resulted was a function of fishing intensity, the fishery vulnerability curve, and relative vulnerability to cannibalism. Average annual fishery yields (catches) more than five times the tonnage of the present fishery were simulated. The principal cause of these high values appeared to be density dependent changes in natural mortality and growth rates. In some cases, increased catches also resulted in increased variability in the size of annual catches, decreased body size of harvested pollock, and increased variability of plankton biomasses. These results were sensitive to parameter values.

Suggestions are given for future studies concerning the biology, ecology, modeling, and management of walleye pollock, in order to reduce uncertainty in parameter values and improve model validity.

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1. INTRODUCTION

In a previous report, Knechtel and Bledsoe (1981) described the numerical simulation model POL and a reference set of initial conditions and parameters. The present report discusses calibration of POL, validation, and some simulation exercises.

As described in Knechtel and Bledsoe (1981), the purpose of these investigations was to study the qualitative dynamics of an exploited cannibalistic fish population (specifically, Bering Sea walleye pollock, *Theragra chalcogramma*) as represented by an age-structured model with mechanisms connecting energy flow, recruitment, mortality, and fecundity in a manner in which they may be connected in the real world. The model is a hypothesis about the way in which an animal may partition energy among various life processes. For study purposes it was necessary to imbed the animal model in a simplified ecosystem including phytoplankton, copepod, and euphausiid populations as food sources. The animal model contains up to 20 age-classes of walleye pollock. A size-selective fishery for walleye pollock is also included. A computer program was developed to implement the model, which enabled exploration of its dynamics.

Section 2 of this report describes the calibration procedure used to modify the preliminary version of POL and its set of initial conditions and parameters. Section 3 contains comparisons of simulated pollock catches, pollock cohort population numbers, pollock lengths, and other Principal System Variables (PSVs) of POL with historical and/or "future" data in order to validate the model. Section 4 describes the design and results of simulation experiments that were done using POL in order to examine some specific questions about the population dynamics of walleye pollock as represented by the model. Section 5 of the report discusses what was learned from the development, calibration, validation, and exercise of POL.

2. MODEL CALIBRATION

Because of the size and complexity of POL, it was first necessary that it be implemented as a computer program so that values for its endogenous variables (i.e., variables at least partially dependent on the state of the model system) could be determined. The model was then calibrated by comparing values of its endogenous variables with simple target criteria for goodness-of-fit developed from historical data concerning the populations modeled. These comparisons were designed to be quick and easy to make, yet still indicative of broader aspects of model behavior that were more difficult to measure. This was necessary because of the many hundreds of computer runs that were needed over a period of more than a year until the criteria were believed to have been adequately met. The calibration procedure was analogous to parameter estimation for a simple statistical model. It was an iterative process consisting of

(1) a computer run of the model for a simulated time period ranging from less than a day to more than 100 years, depending on the behavior examined;

(2) examination of the resulting printouts (listings) of the model's endogenous variables and comparison with the target criteria for goodness-of-fit;

(3) addition of new target criteria if it was believed that some aspect of model behavior should be more carefully observed or controlled;

(4) modification of parameter values, equations, processes, or computer program coding if necessary to remove errors or improve the fit of the model; and

(5) if modifications were made during step 4, repetition of the process starting at step 1.

The model equations and reference set of parameters and initial conditions listed in Knechtel and Bledsoe (1981) were the end result of this model calibration process.

The actual criteria used in the calibration process are discussed in the following subsections, along with discussions of the goodness-of-fit of relevant values of model endogenous variables. These values were calculated after the initial transient model states had died out and nontransient model behavior had become evident. In the following discussion, all target criteria are for nontransient model behavior, unless otherwise stated.

In this study, the term "stationary distribution" is used if the behavior of each relevant PSV was nontransient and periodic with a period of exactly one simulated year, so that within the limits of the accuracy of numerical integration (which for the present parameter set was equal to two or more significant digits) each PSV took on exactly the same value at a given time of a simulated year from 1 year to the next. This is further described in Appendix A. This usage of stationary distribution is analogous to the way Keyfitz (1977:5,170) used the term "stationary population," or the way Laevastu and Larkins (1981:75) used the term "equilibrium biomass." Figure 1 shows examples of initial transient states and the eventual occurrence of a stationary distribution for several endogenous model variables simulated using the reference set of parameters and initial conditions.

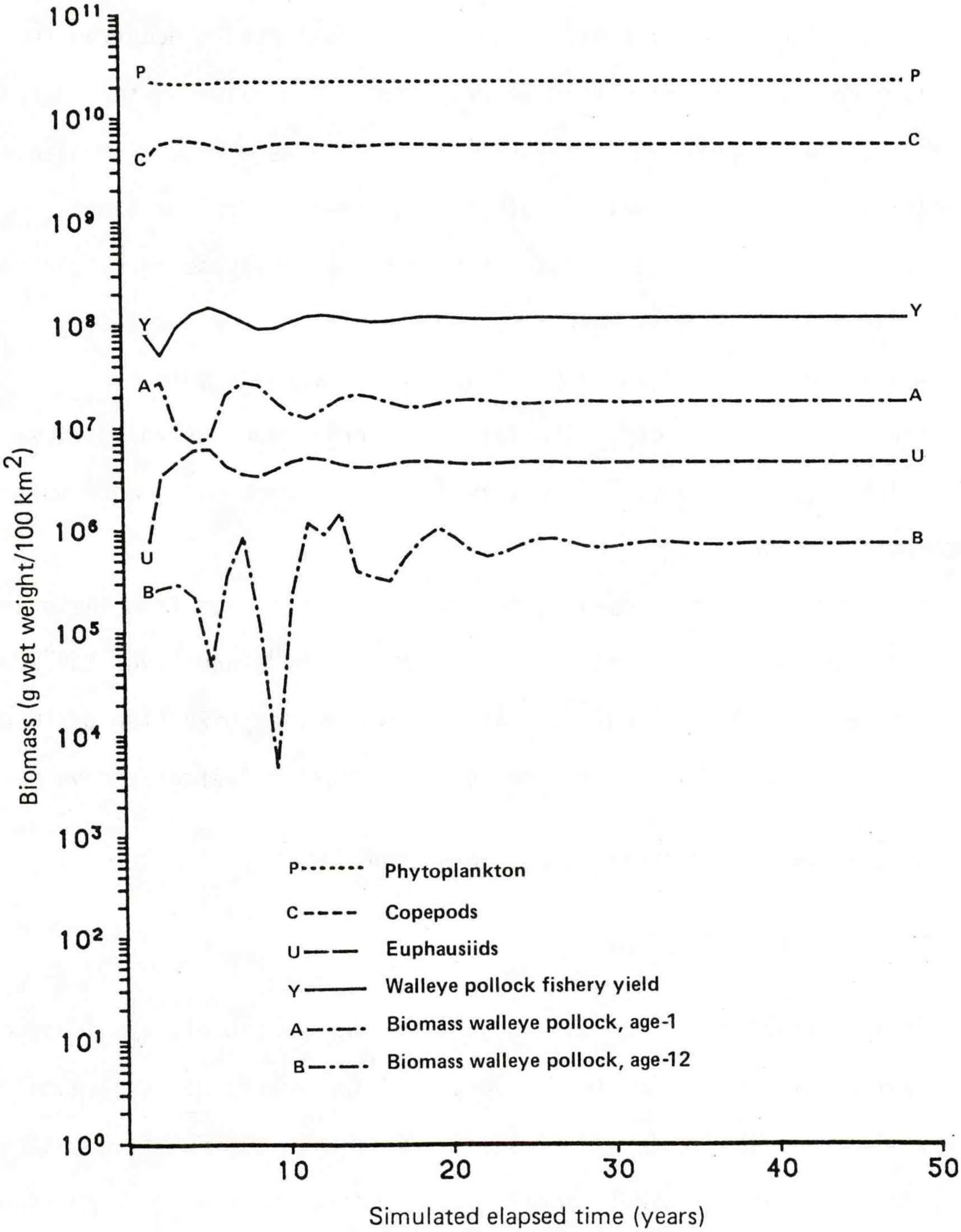

Figure 1.--Biomass versus time graph of some endogenous model variables. Variables were graphed once per simulated year on 13 May; annual periodicities are not shown. Phytoplankton biomasses were calculated assuming 1 gC = 20 g wet weight.

For the reference set of parameters and initial conditions, initial transient fluctuations faded out and a stationary distribution occurred for all the PSVs after about 47 simulated years, so model behavior in the 48th and 49th yr was used to judge how well the target criteria were met. The adequacy of the goodness-of-fit of POL was a subjective judgment. Because some endogenous variables fit the data better than others, it may be expected that the present version of POL will model some aspects of pollock population dynamics, pollock growth, and surrounding ecosystem dynamics more realistically than other aspects. The target criteria represented multiple goals for model behavior, so it is not surprising that some goals were more nearly attained than others.

As much as possible, data used to calibrate the model was from the outer shelf domain of the eastern Bering Sea, at about lat. 56^{o}N and long. 169^{o}W. The area modeled was 100 km^2. Unless stated otherwise, an effective depth of 50 m was assumed for calculation of biomass concentration (weight per volume).

2.1. Goodness-of-Fit Criteria for Zooplankton

2.1.1. Summer Average Zooplankton Biomass

The target criterion for the average summer zooplankton biomass (copepod and euphausiid biomass simulated from 1 June to 1 September) was the range of summer averages given in Motoda and Minoda (1974:fig. 10.10) for five subareas which included parts of the middle shelf, outer shelf, and oceanic domains of the eastern Bering Sea. This range was 35.0-67.1 g/m^2 or 0.438-0.873 g/m^3 wet weight, which was calculated from Motoda and Minoda's values of 35.0 g/m^2 in an 80-m water column and 52.4 g/m^2 in a 60-m water column.

Using the values for the cumulative copepod and euphausiid biomasses, $VCUM_1$ and $VCUM_2$ (detailed definitions of variables are given in Knechtel and Bledsoe 1981:table A-1), the actual simulated summer average zooplankton biomass in the area modeled in simulated year 49 was calculated to be 5.77×10^9 g. This is equivalent to 58 g/m^2 assuming a model area of 100 km^2, or 1.15 g/m^3 assuming an effective depth of 50 m. Thus the model value produced was reasonable in terms of zooplankton biomass per unit area. In view of the amount of variation presumably present in Motoda and Minoda's (1974:fig. 10.11) estimates, the model value was reasonable (though perhaps slightly high) in terms of zooplankton concentration (weight per unit volume).

2.1.2. Annual Minimum Zooplankton Biomass

Data discussed by Meshcheryakova (1970a,b) indicated that the minimum zooplankton biomass would normally occur just before the beginning of biological spring, which occurs in April in the southeastern Bering Sea (Meshcheryakova 1970b:115). In the zone "adjacent to the shallows" (apparently in the oceanic or outer shelf domain), the average zooplankton biomass (wet weight) was 0.074 g/m^3 in February-March 1960 and 0.062 g/m^3 in April 1962 (Meshcheryakova 1970b:109,114). Assuming these values were the minimum zooplankton biomasses for those years, and assuming that annual minimum values are normally distributed, a two-sided 90% confidence interval calculated from these two values is 0.014-0.122 g/m^3.

In simulated year 49, the minimum zooplankton biomass was 1.29×10^8 g, equivalent to 1.29 g/m^2 wet weight or 0.0258 g/m^3 wet weight assuming a model area of 100 km^2 with an effective depth of 50 m. These values are within the estimated confidence interval. The minimum zooplankton biomass occurred between 1 April and 1 May in the model in year 49, so the timing is reasonable. However, assuming that zooplankton have an average chemical composition of 0.052 gC/g wet weight (Mullin 1969:295), then 1.29 g/m^2 is equivalent to 0.067 gC/m^2. This is about 5 to 17 times smaller than the corresponding values estimated about 1 April 1976 for the oceanic and outer shelf domains (Cooney 1981:fig. 57-8).

2.2. Goodness-of-Fit Criteria for Pollock

2.2.1. Pollock Numbers and Mortalities

2.2.1.1. Population Sizes of Pollock Cohorts 3-13--As a target criterion, the nontransient simulated population sizes of individual pollock cohorts 3-13 (age-classes 2-12) on 1 September were compared to the corresponding minimum and maximum estimates of the population sizes of individual pollock age-classes in 1970-78. These ranges were taken from Low (1979:table 7), who made estimates of age-class sizes using virtual population analysis and reported pollock catch data from 1973-78 (Low 1979:table 5). In order to compare the model population sizes (assumed to occupy an area of 100 km^2) with the population sizes estimated by Low, it was assumed that the effective area occupied by the pollock populations he measured was 10^6 km^2. This target criterion for pollock cohort population numbers was met in simulated year 49, as shown in Table 1. However, these comparisons should be regarded as only approximate estimates of model goodness-of-fit for the following reasons.

1) The pollock population measured by Low almost certainly had a nonstationary age distribution due to changes in fishing pressure during the time period 1970-78 (values Low used for terminal fishing mortality acting on

Table 1.--Comparisons of nontransient simulated walleye pollock cohort population numbers on 1 September, with minimum and maximum cohort numbers estimated by Low (1979:table 7) for the years 1970-78.[a]

Cohort	Minimum population size estimated by Low (10^6)	Model estimate of population size ($10^6/10^6$ km^2)	Maximum population size estimated by Low (10^6)
3	4,500	5,100	16,000
4	3,000	4,000	8,100
5	1,200	1,900	5,100
6	620	910	3,400
7	320	450	2,200
8	140	230	1,300
9	66	110	860
10	44	56	390
11	8	28	130
12	6	13	47
13	4	4.2	26

[a] Numbers were rounded to two significant digits. Model estimates are values which resulted from the reference set of parameters and initial conditions after stationary conditions occurred.

different year classes of pollock ranged from 0.3-0.8 year^{-1}). Consequently his estimates probably contain variation due to actual changes in the age distribution of the measured population, in addition to the usual unavoidable variation due to measurement error. Thus the measured population and the simulated population might have differed because the simulated population had a stationary distribution and was acted upon by a constant maximum fishing mortality of 0.3 year^{-1}. (A comparison of Low's values with a simulated nonstationary pollock population acted upon by varying fishing mortality is described in Section 3.2.)

2) The effective area occupied by the pollock populations measured by Low is uncertain. As discussed in the section on initial conditions in Knechtel and Bledsoe (1981), this area could conceivably range from about 0.56×10^6 km^2 to more than 1.2×10^6 km^2, which proportionately changes any population density estimates derived using Low's values.

3) Low (1979) did not present confidence intervals or other indications of the amount of possible error in his estimates (this may not have been possible with available data, techniques, and resources), although he did find that his results were insensitive to some changes in the assumed natural mortality rates (Low 1979:4-5). This makes it difficult to judge the significance of differences between Low's estimates and the model estimates.

4) The catch statistics used by Low may have been underreported (a more detailed discussion of this is contained in a subsequent section on the validity of annual pollock fishery yield). This could cause errors in estimated population numbers.

2.2.1.2. Total Mortality of Pollock Cohort 5--During the model calibration process it was noticed that simulated pollock in cohort 5 (age-class 4) often experienced relatively high values of starvation mortality after spawning (on each simulated 23 April) until about June, for at least some sets of parameters. This was also often the case in the model for cohort 4. The range 0.56-1.48 year^{-1} was therefore used as a target for the total instantaneous mortality rate (including all simulated sources of mortality) calculated from the population size of cohort 5 on 1 August and the population size of cohort 6 on the next 1 August. This range was estimated from fishery survey data from 1973 to 1978 presented by Smith (1981:table 33-3). Data was excluded from a 1-yr period, 1975-76, in which there was an apparent net immigration of pollock (of what became cohort 6) into the survey area.

This target was met in the model during the simulated year beginning 1 August, year 48, when the total instantaneous mortality rate for cohort 5 was 0.71 year^{-1}. This included some starvation mortality (which occurred after spawning until about June). Since the energy demand of spawning caused the starvation mortality, it could also be considered "spawning stress mortality." If more food had been available prior to the spawning period, the starvation mortality would not have occurred, indicating a food supply limitation existed for simulated pollock of this age.

2.2.2. Pollock Lengths

2.2.2.1. Length of Pollock in Cohort 1--The targets for simulated lengths of pollock in cohort 1 (age-class 0) from hatching (13 May) until early March of the next simulated year were the ranges for lengths of that age-class at the different times of the year shown in Cooney et al. (1979:fig. 19). This target was essentially met in the model for simulated years 48-49, as shown in Figure 2.

2.2.2.2. Length of Pollock in Cohort 3--The target for the fork length (FL) of pollock in cohort 3 on 1 September (age 2.3 yr) was 32.5 cm. This was approximately the expected fork length of pollock of that age calculated using the length-age relationship

$$\text{Length} = 60 \times [1 - e^{-0.37 \times (\text{Age} - 0.18)}], \qquad (1)$$

where length is measured in centimeters and age is measured in years. This relationship is similar to those in Pereyra et al. (1976:table IX-21).

This target was met in the model for 1 September of simulated year 49, when the fork length of pollock cohort 3 was 33.0 cm.

2.2.2.3. Maximum Pollock Length--The target for the maximum fork length of pollock in the model on 1 September was 50 cm or greater, with a preferred range of 65-80 cm (Pereyra et al. 1976:table IX-21). On 1 September of simulated year 49, the maximum length of pollock was 57.1 cm (the maximum length during the previous year was about 57.3 cm), so this criterion was met in the model, although the maximum length was lower than preferred.

2.2.3. Pollock Weights

The goodness-of-fit of the weights of pollock was checked by requiring that the maximum condition index for any cohort i (measured using model variable GCN_i) be no more than 1.5. This seemed to be a reasonable maximum condition index for pollock down to about 14 cm FL from data graphed in

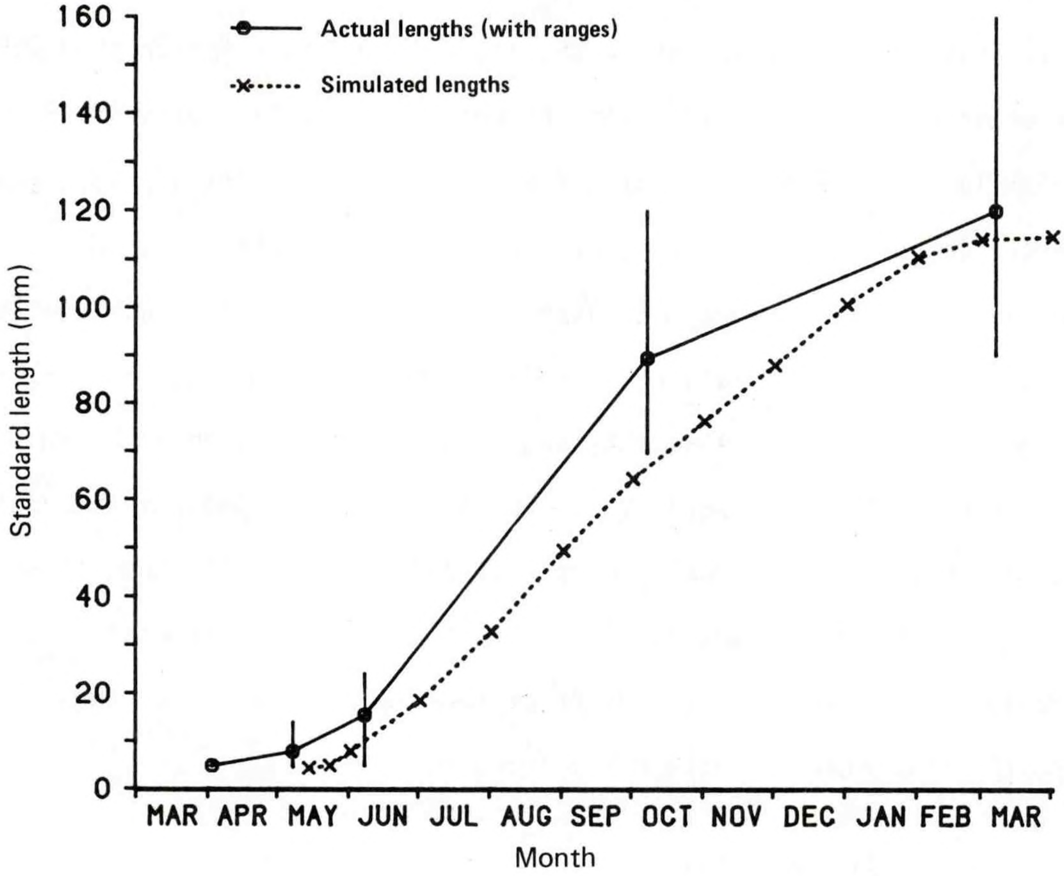

Figure 2.--Simulated nontransient growth in length of walleye pollock <1-yr-old compared with actual lengths (Cooney et al. 1979: fig. 19). Actual lengths were measured after the pollock had been preserved in formalin.

Pereyra et al. (1976:fig. IX-35), and it was assumed to also apply to shorter pollock. This criterion was met in the model for pollock longer than 0.52 cm, because their maximum condition index throughout simulated years 48-49 was 1.26. Simulated newly hatched pollock had a condition index of 2.87, which represented energy in their yolk sacs, but by the time they reached 0.52 cm their condition index decreased to 1.22. Despite the fact that this target was met, simulated weights of pollock at lengths of about 0.7-4.5 cm showed poor agreement to the weight-length relationship given in Haryu (1980). This relationship seems to indicate that larval and juvenile pollock in this length range are actually about 1.9-3.1 times heavier than those of comparable lengths in the model. This error was probably associated with inaccuracies in the underlying energetics model which was formulated principally from relations determined for adult animals.

2.2.4. Maximum Pollock Ages

As a check on the total cumulative sources of mortality acting on pollock, the target maximum pollock age in the model was 13-17 yr (Pereyra et al. 1976:381). This goal was met in the model for simulated year 49, at which time maximum survival was about 16.2 yr.

2.2.5. Total Biomass of Pollock Cohorts 3-13

As a check on the overall goodness-of-fit of pollock weights and population numbers, the target range for total biomass of pollock cohorts 3-13 (age-classes 2-12) on 1 September was 5.25-7.83 million metric tons (t), as estimated by Low (1979:table 7).

This criterion was met in the model using the reference set of parameters and initial conditions. On 1 September of simulated year 49, the biomass of cohorts 3 through 13 (model variable B313) was 7.19×10^8 g for the model area of 100 km^2. This was equivalent to a biomass of 7.19 million t, assuming that the pollock population measured by Low occupied an effective area of 10^6 km^2. Using the reference set of parameters and initial conditions, the biomass of pollock cohorts 3-13 showed a yearly periodicity in the model (see Figure 3) ranging from a high of about 7.4×10^8 g/100 km^2 (equivalent to 7.4 million t) around 1 October to a low of about 3.8×10^8 g/100 km^2 (equivalent to 3.8 million t) just before the cohorts were updated on 13 May.

2.2.6. Annual Pollock Catches

As a check on the goodness-of-fit of the fishery vulnerability curve and fishing mortality rates in the model, as well as the goodness-of-fit of the pollock weights and numbers, the target annual pollock catch in the model was 10^6 t/10^6 km^2, because Low (1979:6) thought 10^6 t was close to the long-term equilibrium yield under fishing conditions existing in 1976-78. (This was also thought to be the case for 1979-80, see Bakkala, Wespestad, and Low (1981:20)).

This criterion was met in the model using the reference set of parameters and initial conditions. The simulated equilibrium annual catch for the fishing "season" ending in model year 49 was 1.13×10^8 g for the 100 km^2 area modeled, equivalent to an annual catch of 1.13×10^6 t (assuming that the effective area for the fish population was 10^6 km^2). This also assumes that actual pollock must either migrate through or concentrate in the area actually

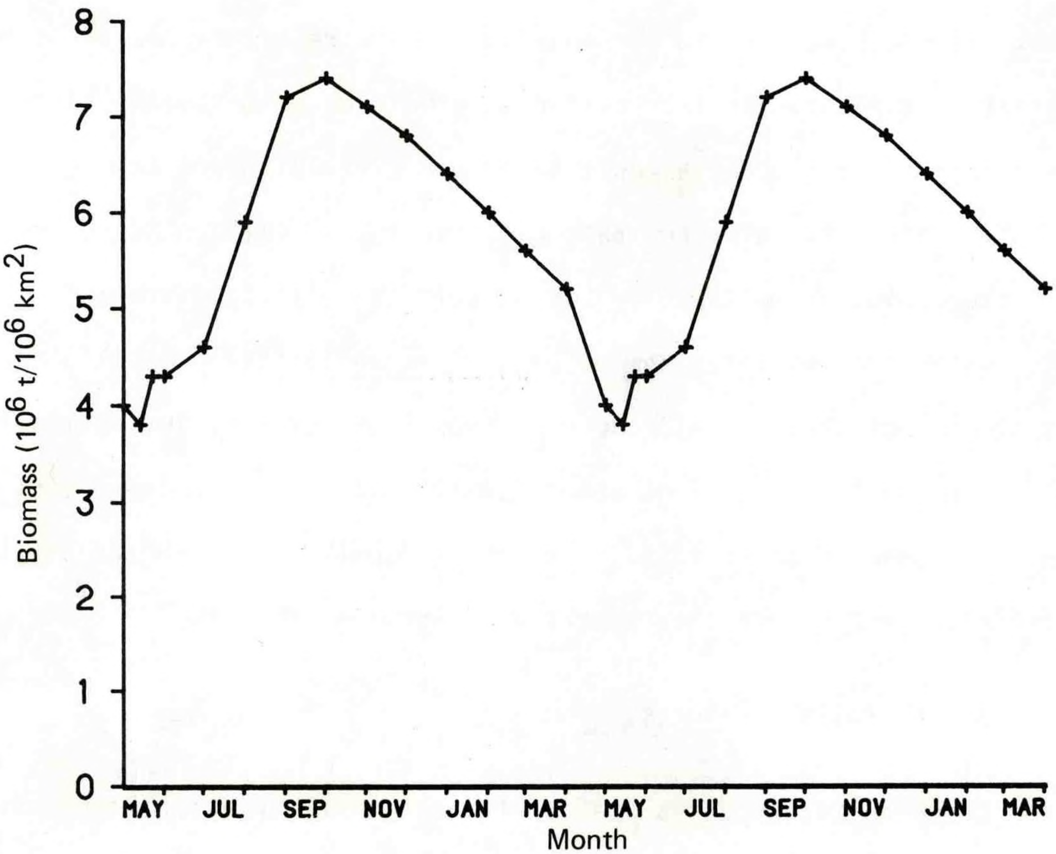

Figure 3.--Total nontransient biomass of walleye pollock cohorts 3 through 13 showing annual periodicity.

fished, because statistical areas for the Bering Sea pollock fishery cover only about 0.56×10^6 km^2. This is discussed in the section on initial conditions of Knechtel and Bledsoe (1981).

3. MODEL VALIDATION

For the purposes of this study, model validation means the comparison of significant aspects of model behavior with data about the behavior of the real system to give the researcher insights into similarities and differences, i.e., when the model is valid and invalid.

> "In fact, it is the central tenet of modern scientific method that hypotheses, including models, can never be proved right; they can only be proved wrong.... Provisional acceptance of any model implies not certainty, but rather a sufficient degree of belief to justify further action. In practice, the problem is one of model invalidation--of setting the model at risk so as to suggest the limits of its credibility. The model is subjected to a range of tests and comparisons designed to reveal where it fails." (Holling 1978:95)

Validation is a process intended to produce a sufficient degree of confidence in a model (cf. above, "sufficient degree of belief") so that it can be used for a specific purpose ("further action"). In this study, the original purpose was the projection of the probable qualitative behavior of a fish population. Qualitative behavior refers to attributes such as stationary conditions vs long-term periodicity vs chaos, or increased fishery yields vs decreased yields. This is not as stringent as the projection of quantitative behavior, which refers to specific numeric values achieved.

As used in this study, the chief feature which distinguishes model validation from model calibration is difference in purpose. Comparisons made to data during validation of the model were intended to reveal model inaccuracies, while comparisons made to data during calibration were part of a process to correct model inaccuracies by model modifications, including parameter adjustments. The comparisons made to calibrate the model were much quicker to perform than the comparisons made for model validation, but not as detailed. In most cases, the data sets used for model calibration were also different from the data sets used for model validation. However, the comparisons made to validate the model may eventually lead to model modification, so model validation can become part of the calibration process.

The behavior generated by a model may contain statistically significant differences from the behavior of the actual system. Nonetheless, if some aspects of model behavior conform sufficiently well to the behavior of the actual system, the model is still useful and can be considered "valid" for some purposes (Silvert 1981:671; Caswell 1976:319-321). Even though the comparisons made to validate POL show some statistically significant differences between its behavior and the measured behavior of the eastern Bering Sea pollock population, the comparisons also demonstrate many similarities. In these cases, POL can provide useful qualitative insights into the behavior of pollock population dynamics, as well as useful quantitative approximations. Since no model is ever completely valid, a judgment must be made on the basis of known inaccuracies whether to use a model for a particular purpose. More realistically, a judgment is often required whether any alternative investigative method is available (e.g., another model) which is more likely to be sufficiently accurate for the purpose at hand. It is frequently the case in management of a fishery that the "best available" methods to decide on a course of action must be used despite known inaccuracies, because the consequences of indecision and inaction may be as profound as the consequences of any particular course of action chosen.

Validation may be categorized as either predictive or historical. In predictive validation, comparisons are made to data measured sometime after the data used to calibrate the model. Naylor et al. (1966:318) stated, "It is our position that the ultimate test of a computer simulation model is the degree of accuracy with which the model predicts the behavior of the actual system (which is being simulated) in the future."

In historical validation, comparisons are made to data measured prior to, or at the same time as, the data used to calibrate the model. For example, if the most recent part of a time series was used to calibrate a model, the earlier part can be used to validate the model. Under some circumstances, the data used in validation may legitimately include data used to calibrate the model (Naylor et al. 1966:316-317). This may occur if the data were used to estimate parameters for a part of the model independently of the whole, because resultant behavior may be quite different when the part operates jointly with the whole.

In order to compare POL with an actual system, simulations were made of the eastern Bering Sea pollock population during the time period 1964-80. Prior to 1964, there was almost no fishery for eastern Bering Sea pollock, though there might have been unreported incidental catches which were largely discarded (Pruter 1973). Beginning in 1964, both effort and catch levels for pollock greatly increased in the eastern Bering Sea, with annual reported catches reaching a maximum in 1972. Catches declined after this, followed by apparent stabilization of catch levels in 1976-80 (Bakkala, Wespestad, and Low 1981). Table 2 gives the total annual eastern Bering Sea pollock catches, U.S. procedure catch per unit effort (CPUE) indices, and estimated fishing effort for the years 1964-80.

Table 2.--Statistical summary describing eastern Bering Sea walleye pollock fisheries, 1964-80.

Year	Total[a/] reported catch (t)	U.S. procedure[b/] pair trawl CPUE index	Nominal[c/] fishing effort	Estimated[d/] F ($year^{-1}$)	Simulated[e/] catch (10^6 t/10^6 km^2)
1964	174,792	9.5	18	0.048	0.25
1965	230,551	18.3	13	0.033	0.17
1966	261,678	23.6	11	0.029	0.14
1967	550,362	21.3	26	0.067	0.33
1968	702,181	23.8	30	0.077	0.37
1969	862,789	31.5	27	0.071	0.34
1970	1,256,555	18.7	67	0.17	0.80
1971	1,743,763	14.2	120	0.32	1.3
1972	1,874,534	14.2	130	0.34	1.3
1973	1,758,919	8.6	200	0.53	1.7
1974	1,588,390	10.4	150	0.40	1.2
1975	1,356,736	9.3	150	0.38	1.2
1976	1,177,822	9.4	130	0.33	1.1
1977	978,370	8.6	110	0.30	1.2
1978	979,424	9.4	100	0.27	1.1
1979	913,881	9.4	97	0.25	1.0
1980	963,168	7.6	130	0.33	1.3

a/ From Bakkala, Wespestad, and Low (1981:table 1), except 1980 value was a preliminary estimate from S. Murai (Northwest and Alaska Fisheries Center, 2725 Montlake Blvd. E., Seattle, WA 98112; pers. commun.). t = metric tons.

b/ Units are t/1,000 pair trawl horsepower-hours trawled. From Bakkala, Wespestad, and Low (1981:table 2), except 1980 value is from Low and Berger (1981:table 2).

c/ Units are 10^6 pair trawl horsepower-hours trawled. Estimated by dividing the total reported catch by the U.S. procedure CPUE index. Values have been rounded.

d/ Estimated by multiplying the unrounded estimated nominal fishing effort in the previous column by 0.0026. Values have been rounded.

e/ Catches were simulated using the unrounded values for F given in the previous column. Simulated catch values have been rounded.

The eastern Bering Sea pollock population almost certainly did not have a stationary age distribution during the time period 1964-75, in part due to changes in fishing effort which occurred. In contrast, as previously discussed in this study, the model and its behavior (including fishery yields) were almost entirely calibrated under stationary conditions. The only exception to this was the parameter q, called XETOF in Knechtel and Bledsoe (1981), which was a multiplier (catchability coefficient) that could optionally be used to convert nominal fishing effort into instantaneous fishing mortality rates. Parameter q was estimated by fitting simulated catch data from 1973-78 to actual catch data from those years; this is described in more detail later in this section.

In order to determine initial starting conditions for the simulations, it was assumed that there was negligible pollock fishing mortality in years previous to 1964. The model was run using the reference set of parameters and initial conditions, but with the fishing mortality rates (array F) set equal to 0, until a stationary distribution occurred for the model PSVs. The values of this stationary distribution on a simulated 1 September were used as the initial starting conditions for the model on simulated 1 September 1963 (Tables 3 and 4). Then a series of different model runs were made simulating the pollock population from 1 September 1963 to 1 January 1981, but using a different value of q for each simulation. The values used for q ranged from 2.0×10^{-6} to 3.8×10^{-6} year^{-1}/(1000 pair trawl horsepower-hours trawled) with a step of 0.2×10^{-6} year^{-1}/(1000 pair trawl horsepower-hours trawled). The fishing season was assumed to begin and end on 1 January each simulated year. The nominal fishing effort for each simulated year 1964-80 was estimated by dividing the reported annual catch of pollock in the eastern

Table 3.--Initial starting conditions of differential equations describing plankton biomasses, number of walleye pollock eggs, and fishery catch (starting 1 September 1963).[a]

Equation	Starting conditions
Phytoplankton biomass	2.3619573×10^8 g C/5 km^3 (= 47.2 micrograms C/liter, 47.2 g wet weight/m^2)
Copepod biomass	3.3504442×10^8 g wet weight/5 km^3 (= 6.70×10^{-2} g wet weight/m^3, 3.35 g wet weight/m^2)
Euphausiid biomass	4.5727252×10^8 g wet weight/5 km^3 (= 9.15×10^{-2} g wet weight/m^3, 4.57 g wet weight/m^2)
Surviving pollock eggs	0 per 5 km^3
Pollock fishery catch (yield)	0 g/5 km^3

a/ Conversions to various units are also shown. Phytoplankton was assumed to contain 1 g C per 20 g wet weight. An effective depth of 50 m was assumed for all conversions of area to volume.

Table 4--Initial starting conditions of differential equations describing fork lengths, body weights, and population numbers of walleye pollock (starting 1 September 1963).[a]

Pollock cohort i	Length L_i (cm)	Weight W_i (g)	Number N_i (No./5 km^3)	Number N_i (No./10^6 km^2)	Biomass[b] B_i (t/10^6 km^2)
1	5.645	0.78295	5.5238×10^7	5.5×10^{11}	4.3×10^5
2	20.158	69.001	4.7990×10^5	4.8×10^9	3.3×10^5
3	33.164	313.36	3.5310×10^5	3.5×10^9	1.1×10^6
4	40.46	574.73	2.8905×10^5	2.9×10^9	1.7×10^6
5	44.99	786.22	1.8476×10^5	1.8×10^9	1.5×10^6
6	47.71	960.34	1.2005×10^5	1.2×10^9	1.2×10^6
7	49.70	1,104.7	8.0467×10^4	8.0×10^8	8.9×10^5
8	51.24	1,223.7	5.3935×10^4	5.4×10^8	6.6×10^5
9	52.44	1,321.8	3.6160×10^4	3.6×10^8	4.8×10^5
10	53.39	1,402.0	2.4242×10^4	2.4×10^8	3.4×10^5
11	54.15	1,466.8	1.6249×10^4	1.6×10^8	2.4×10^5
12	54.74	1,516.7	9.9478×10^3	9.9×10^7	1.5×10^5
13	55.20	1,555.8	4.5108×10^3	4.5×10^7	7.0×10^4
14	55.56	1,586.5	1.5157×10^3	1.5×10^7	2.4×10^4
15	55.84	1,610.3	4.1336×10^2	4.1×10^6	6.7×10^3
16	56.07	1,628.5	1.1283×10^2	1.1×10^6	1.8×10^3
17	56.25	1,642.5	3.0809×10^1	3.1×10^5	5.1×10^2
18	56.38	1,653.2	8.3873	8.4×10^4	1.4×10^2
19	56.49	1,661.4	2.2780	2.3×10^4	3.8×10^1

a/ Conversions to various units are also shown.

b/ $B_i = W_i \times N_i$.

Bering Sea by the U.S. procedure pair trawl CPUE index (Table 2). This estimate of nominal fishing effort was multiplied by q to calculate the instantaneous fishing mortality rate (array F) which was used during that year in the simulation.

The simulated catch of pollock was assumed to have been from a pollock population occupying an effective area of 100 km^2. It was also assumed that the effective area occupied by the pollock population exploited by the actual fishery was between 0.4×10^6 and 1.4×10^6 km^2. Using the model catches (converted to different assumed effective areas) as predictors of the reported catches, the sum of squares of the residuals for the years 1973-78 was calculated for each simulation run. The best estimate of q was taken to be the value which minimized the residual sum of squares calculated for 1973-78 (Table 5) using an estimate of effective area of 1×10^6 km^2. This was the effective area previously used in calibration of the stationary behavior of the model. The resulting "best" estimate of q was 2.6×10^{-6} $year^{-1}$/(1000 pair trawl horsepower-hours trawled).

These estimates of q and effective area were also close to the values 2.4×10^{-6} and 1.2×10^6 which produced the minimum residual sum of squares for the time period 1964-79 shown in Table 6, although this did not influence the original choice of values.

A number of simulation runs were then made for portions of the time period 1964-80, using the value $q = 2.6 \times 10^{-6}$ $year^{-1}$/(1000 pair trawl horsepower-hours trawled). As a measure of the validity of POL, values of principal system variables (PSVs) during these runs were compared with actual data; these PSVs are listed in Table 7 together with a summary of the results

Table 5.--Residual sum of squares (10^{10} t^2) between reported and simulated catches for 1973-78 as a function of effective area and catchability coefficient.

Effective area (10^6 km^2)	Catchability coefficient (q) a/									
	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8
0.4	510	480	452	427	403	380	360	340	323	304
0.6	307	274	242	216	192	171	152	136	121	108
0.8	158	128	102	82	66	54	45	40	38	38
1.0	61	42	30	24	25	29	39	54	71	96
1.2	18.1	17.6	26	42	68	96	133	176	221	280
1.4	28	54	91	136	195	255	328	407	489	590

a/ Units: 10^{-6} $year^{-1}$/(1,000 pair trawl horsepower-hours trawled).

Table 6.--Residual sum of squares (10^{10} t^2) between reported and simulated catches for 1964-79 as a function of effective area and catchability coefficient.

Effective area (10^6 km^2)	Catchability coefficient (q) a/									
	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8
0.4	1,149	1,091	1,034	984	936	892	850	810	775	738
0.6	776	707	642	585	533	487	444	405	372	339
0.8	486	418	356	307	264	228	198	174	156	143
1.0	278	223	179	148	128	115	112	117	128	148
1.2	152	123	108.9	110	126	149	186	233	286	355
1.4	109.1	118	146	192	257	330	420	523	632	764

a/ Units: 10^{-6} $year^{-1}$/(1,000 pair trawl horsepower-hours trawled).

Table 7.--Summary of model validity.

Principal system variables (PSVs)		Validity
YLD	Annual pollock fishery yield (catch)	Similar to reported values (R^2=0.65). Residuals were serially correlated.
N_2-N_{16}	Pollock population numbers (age > 1 yr)	Similar to estimated values (R^2=0.73 and 0.83), but statistically significant differences existed attributed to time period of measurement and differences in age structure.
L_1	Pollock lengths (age < 1 yr)	Qualitatively similar to measured lengths but also consistently slightly shorter than expected.
L_2-L_{16}	Pollock lengths (age > 1 yr)	Similar to measured lengths (R^2=0.84), but statistically significant differences also existed for some age-classes.
W_1	Weights of larval pollock (< about 3.9 cm SL)	Frequently invalid, i.e., consistently less than expected from a measured length-weight relationship.
W_1-W_3	Weights of pollock (5.7-20.7 cm SL)	Similar to measured length-weight data. Slight, but statistically significant, differences also existed.
W_3-W_{11}	Pollock weights (ages 2-10 yr)	Similar to measured data (R^2=0.33), but statistically significant differences existed for some age-classes.
FCF, FCM	Arrays containing the fractions of mature females (FCF) or males (FCM) in each pollock cohort	Reasonably realistic. Because of the use of empirical length-maturity relationships for each sex, the validity of FCF and FCM was dependent on the validity of simulated pollock lengths and on an empirical sex ratio.
ETT, E	Number of pollock ova laid (ETT) or surviving (E).	Qualitative similarities in order of magnitude.
PHY	Phytoplankton biomass.	Qualitatively similar.
COPE + EUPH	Total zooplankton biomass.	Qualitatively similar, but the simulated annual minimum value may be lower than expected from measured data.

of the comparisons. The comparisons are discussed in detail in subsequent sections.

3.1. Validity of Annual Pollock Fishery Yields

Simulated transient pollock catches during 1964-72 (calculated using the "best" estimate of q and effective area) were compared to historical Bering Sea pollock catches. This provided historical validation for the model, because transient catches represented emergent model behavior which was not intentionally produced by the original model calibration process. Also, since pollock catch and population data measured after 1978 were not used in calibration of the model, the comparison of simulated and reported catches for 1979-80 provided predictive validation.

Table 2 shows these simulated pollock catches, converted to units of 10^6 t/10^6 km^2. A plot of the simulated and reported annual pollock catches from Table 2 is shown in Figure 4.

The residual sum of squares (RSSA) of the actual reported catches about their mean was 4.594×10^{12} t^2. The residual sum of squares of the actual catches about the model catches (RSSM) was 1.585×10^{12} t^2, assuming an effective area of 1×10^6 km^2. These results gave a generalized squared correlation coefficient (R^2 = 1 - RSSM/RSSA) of 0.655, which can be interpreted to signify that the model explained 65.5% of the variation of the reported catches about their mean during the years 1964-80. However, the residuals of the reported catches about the model catches (Figure 5) were apparently serially correlated, which indicated the possibility of predictable variations in pollock catches in the years 1964-80 unaccounted for in this simulation.

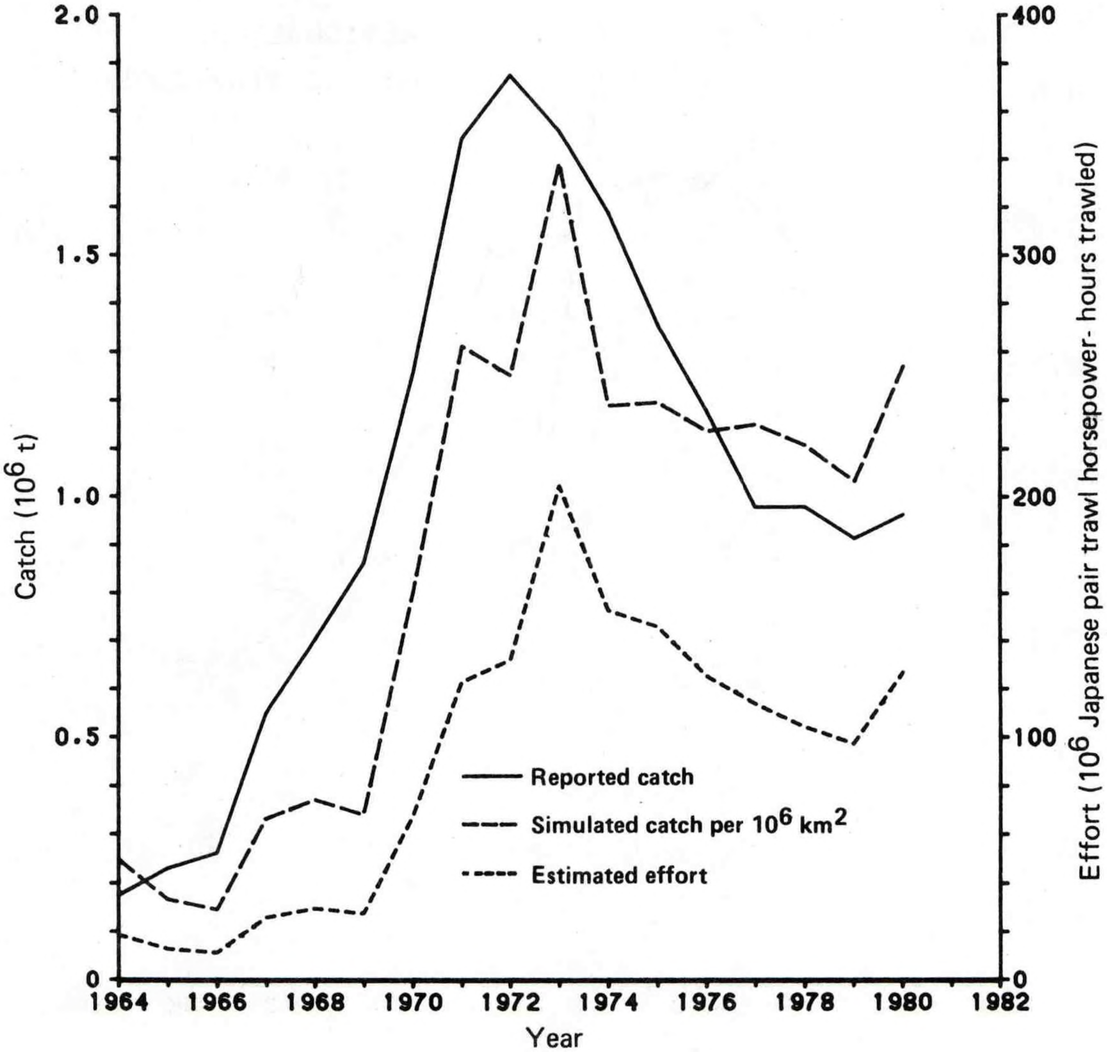

Figure 4.--Reported and simulated annual walleye pollock catches and estimated effort for 1964-80. A constant catchability coefficient was used to determine simulated catch.

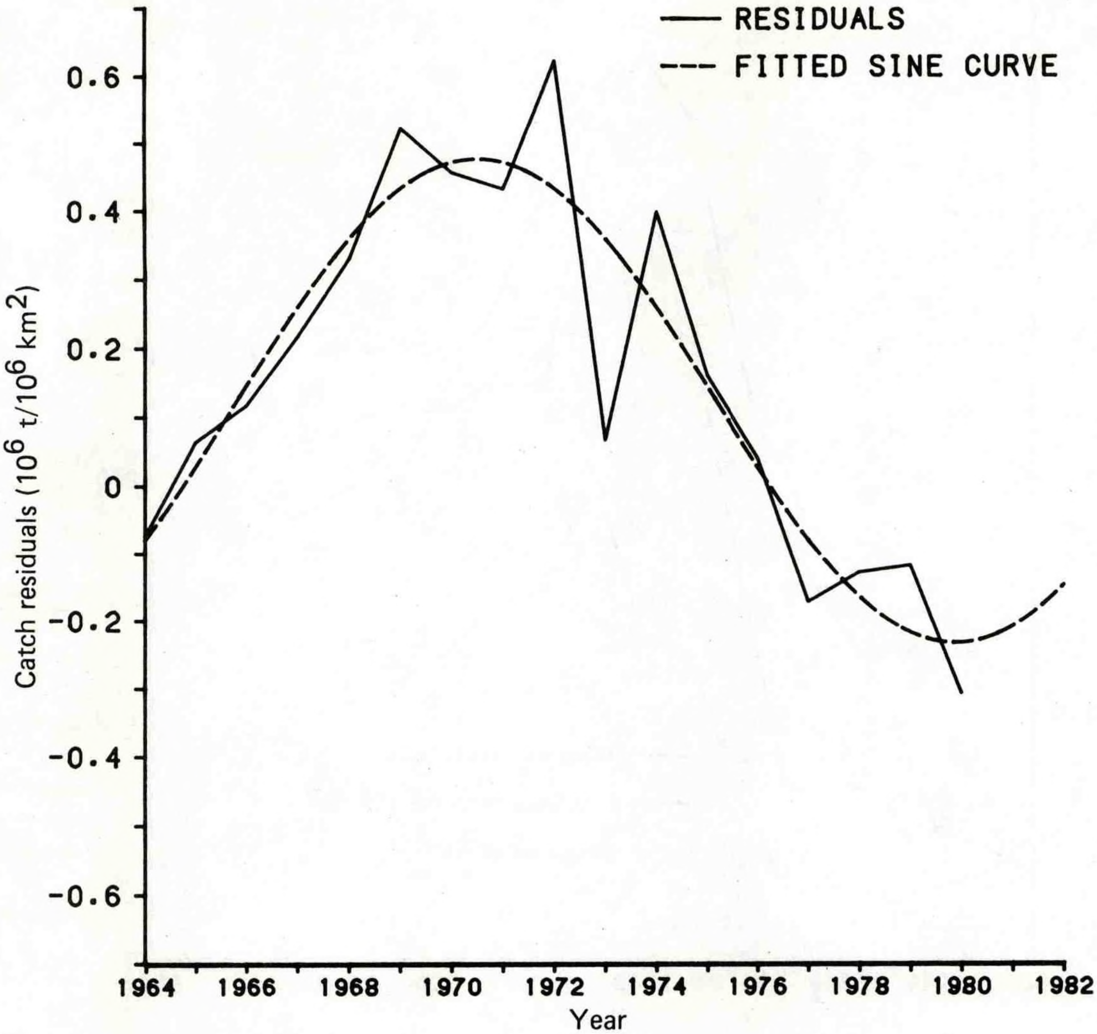

Figure 5.--Annual catch residuals for walleye pollock (reported catch minus simulated catch) for 1964-80, with the least squares fitted sine curve 0.1224 + 0.3550 x sin(0.3347 x (t-1965.8052)).

The mean of the 17 yr of catch data (1964-80) is a very simple model which could be used to predict the expected catch for any given year; in other words, one would simply expect the catch that year to equal the calculated mean. However, this simple model cannot explain (provides no information regarding) any variation in the catches, because it predicts the same catch should occur every year. One would expect an improved model to explain some of the variation in catches which actually occurred. If the model POL is an improvement over the simple model represented by the mean, one would expect RSSM to be smaller than RSSA. In analysis of variance terminology, one would expect a reduction in the residual sum of squares. An F statistic can be used to measure the statistical significance of this reduction, assuming that the underlying errors have an identical normal distribution with a mean of zero and are independent. The serial correlation of the residuals may indicate that the underlying errors were not independent in this case. Nonetheless, the significance of an F statistic provides a useful qualitative measure of the significance of the reduction in residual sum of squares. This is analogous to the use of the F statistic in the forward selection of variables for a linear regression model as described by Draper and Smith (1981:sections 6.4-6.5). Because of the methods used to calibrate POL, it is uncertain how many degrees of freedom (df) should be associated with RSSM in order to calculate an F statistic. Of the 17 yr of catch data analyzed, 6 data points (1973-78) were used for calibration. So it is reasonable to assume the df associated with RSSM is in the range 11 (1 df "used" for each data point used for calibration) to 14 (3 df used). If RSSM has 11 df, the F statistic is (RSSA/16)/(RSSM/11) = 1.993, which is statistically significant at the 87.5% level. If RSSM has 14 df, then the F statistic is (RSSA/16)/(RSSM/14)=2.537, which is statistically significant at the 95.6% level. Thus the null hypothesis that the catches simulated using POL do not fit the data better than the mean is rejected at an approximate significance level of 88-96%, under the assumption that the test is robust with respect to failure to meet any required assumptions. Reported and simulated catches were realizations of processes that were approximately "smooth" or continuous. Correlation of errors is a general characteristic of such situations, and does not necessarily imply model lack-of-fit (Glasbey 1980:135; Bard 1974:section 7-17).

Therefore, there is a reasonable probability that POL is an improved model and explains fluctuations in reported catch levels which could not be explained simply by estimation of a mean catch. This is evidence for the usefulness of POL in prediction of pollock catches resulting from fishing effort within the range of historical effort levels; that is, for instantaneous fishing mortality rates estimated to be less than about 0.53 $year^{-1}$ on the basis of reported catches (Table 2).

Insight into the nature of the serial correlation of the residuals was shown by a periodogram (as defined in Box and Jenkins 1976:section 2.2.1, but normalized so that the ordinates at nonzero frequencies sum to 1). The periodogram is shown in Figure 6. The null hypothesis that the time series of residuals consisted of white noise (i.e., that each residual was independent and had the same normal distribution) was rejected based on a test using Siegel's T_{lambda} statistic (Siegel 1980), with lambda equal to 0.6. It was calculated that $T_{0.6} = 0.527$, which was significant at the 95% level. Thus the time series of residuals could be considered to be periodic. Using Shimshoni's test (Shimshoni 1971), the cycle with a period of 17 yr (the

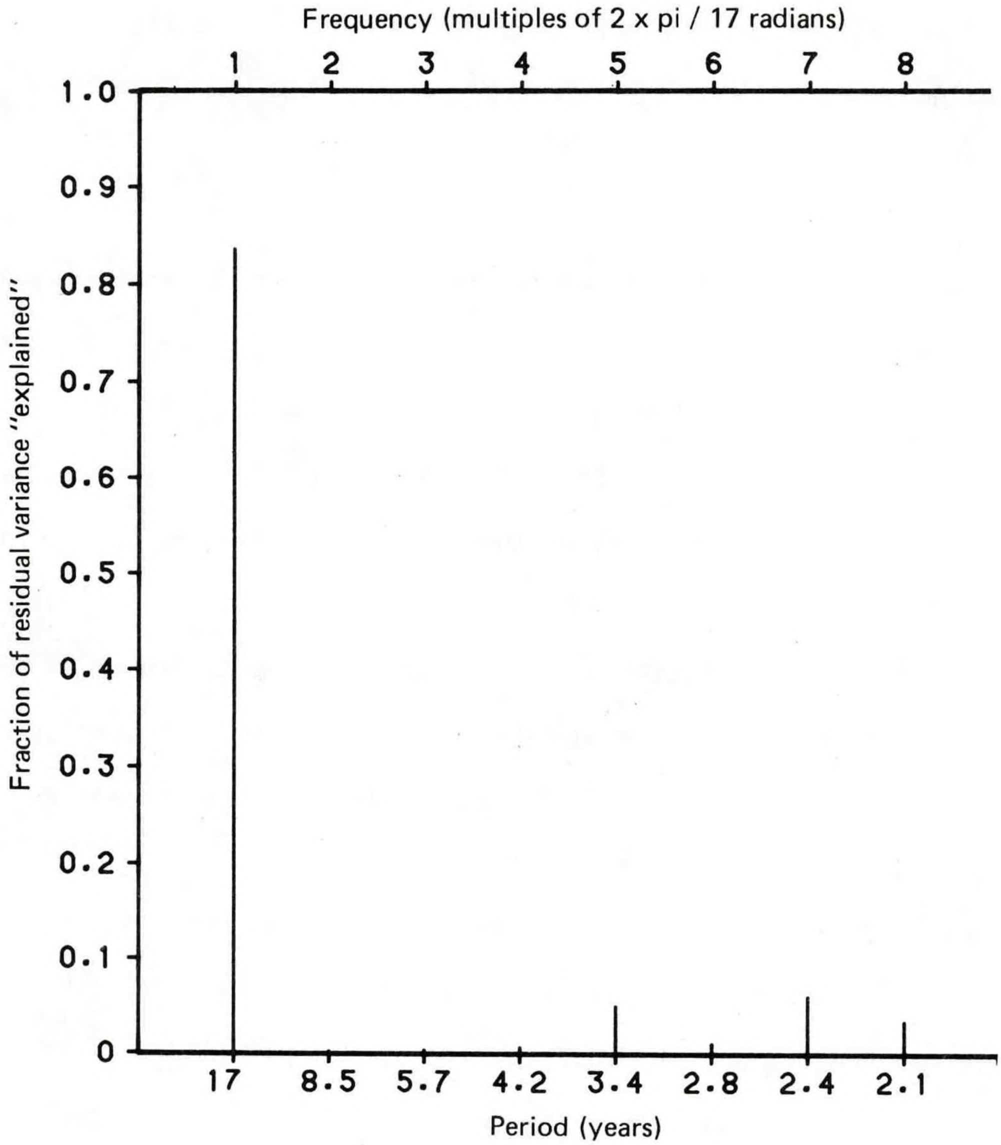

Figure 6.--Normalized periodogram of the annual catch residuals for walleye pollock (reported catch minus simulated catch), 1964-80.

length of the time series) was significant at the 95% level, but the cycles with shorter periods were not significant at even the 50% level.

The cosine curve

$$mu + A \times \cos(omega \times (t - t_0) + phi) \qquad (2)$$

was fit to this data, where mu, A, omega, t_0, and phi are parameters (omega and phi were measured in radians). This cosine curve is shown in Figure 5. The generalized squared correlation coefficient (R^2) was 0.846, and the period of the cosine curve was 18.8 yr. Since this time series of residuals has not gone through even one complete period, the hypothesis that the time series is periodic should be regarded with caution.

Examination of the residuals shows that the catches predicted by POL were consistently lower than the reported catches from 1965-76, but consistently higher than the reported catches in 1977-80. A number of different factors might explain this pattern.

1) Lack of fit of the model POL. This could be due to inappropriate equations or simply the need for better parameters. It could also be that some factors not modeled may be important, e.g., fluctuations in predation rates on pollock from sources other than cannibalism, and competition of pollock for food with species other than euphausiids.

2) Underreporting of catches. French and Horton (1981) reported that, in 1973-74, the tonnage of groundfish (including pollock) caught in the eastern Bering Sea that was logged by six Japanese stern trawlers averaged 23% less than the tonnage estimates of U.S. and Canadian observers. In 1978, the logged tonnage of groundfish caught in the Bering Sea during 1,002 hauls by large Japanese stern trawlers (displacement $\geq$ 1500 gross register tonnage

(GRT)) averaged 19% less than the tonnage estimates of U.S. observers. In that same year, the logged tonnage of groundfish caught during 2,486 hauls by small Japanese stern trawlers (< 1500 GRT) averaged 32% less than the tonnage estimates of U.S. observers. In 1978, only 8.1% of the total fishing effort (vessel months) by Japanese stern trawlers in the Bering Sea and Gulf of Alaska was monitored by U.S. observers. In 1979, the daily catch rate (t/day) of pollock reported by 14 Japanese surimi trawlers increased an average of 38% when a U.S. observer came on board and decreased an average of 21% when the observer left (data from the 2 wk before and after the boarding of the observer were used in these comparisons). Total U.S. observer coverage of foreign fishing activities in the Bering Sea/Aleutian Islands region in 1977-80, is summarized in Nelson et al. (1981a:table 5); French et al. (1982:table 3); and Nelson et al. (1981b:table 3).

Extrapolation using these figures leads to the hypothesis that the total annual catches reported for pollock could have been at least 20-30% less than actual catches. If this was indeed the case, the fishing mortality rates used in POL in the simulation of the fishery may have been too low. Changing them would lead to changes in the simulated dynamics observed.

In 1973, catch quotas were established for pollock fisheries in the eastern Bering Sea (Bakkala, King, and Hirschberger 1981:1031); similar quotas have continued to the present. In addition, beginning in 1977, foreign nations have had to pay fees based in part upon the weight of pollock caught within the 200-mile fishery conservation zone (FCZ) of the United States (Pileggi and Thompson 1980:85,87). These catch quotas and fees may have provided incentives to underreport catches.

Since data from 1973-78 was used to estimate parameter q, additional underreporting beginning in 1977 would cause the value of q to be too low to account for the reported catches before 1977, so that simulated catches would be low in comparison with reported catches before 1977. It would also cause the value of q to be too high to account for reported catches in 1977 and after, so that simulated catches would be high in comparison with reported catches in 1977 and after. With the exception of 1964 (which can be accounted for by other factors discussed later), this pattern of differences between simulated and reported catches actually occurred (Figures 4 and 5), although other factors also could have contributed to the differences.

Pollock population numbers and equilibrium yield estimated by using reported catches from 1973-78 (Low 1979) had an influence on the choice of those parameter values of POL which were estimated under stationary conditions (see Section 2, Model Calibration). Although the simulation being discussed here is not stationary, underreporting of catches still may have led to some model lack-of-fit because of this influence on parameters. Much auxiliary information (such as pollock weight-at-age data) was used to calibrate POL, which in many cases may have reduced any effects that underreporting of catches had on parameter values. However, the calibration process may have led to increased natural mortality rates in POL to compensate for underestimated fishing mortality rates.

3) Decreasing efficiency of the pollock fishery (as measured by amount of fish caught per unit effort) in the years 1973-80 due to fishing regulations. This might account for at least part of the observed trend of reported catches becoming smaller relative to simulated catches in 1973-80.

For example, various regulations have been implemented (Smith et al. 1981:25-27) to reduce incidental catches of prohibited species such as Pacific halibut (Hippoglossus stenolepis), salmon (Oncorhynchus spp.), king crab (Paralithodes spp.), and snow (Tanner) crab (Chionoecetes spp.). These regulations may have also decreased the efficiency of trawl fishing operations for pollock.

4) Changing catchability (due to gear improvements) or fewer discards. Improvements in fishing gear, techniques, skill, technology, and vessels (Low and Berger 1981) particularly may have been a factor in 1964-69, when reported catches increased almost five-fold while estimated effort fluctuated at about the same level (Figure 4; Table 2). Also, as pollock became a primary target of Bering Sea trawl fisheries and new market products were developed, fewer may have been discarded (Pruter 1973:2378).

5) Temperature changes causing changing catchability (due to migrations) and changing growth rates. Pereyra et al. (1976:63-64) reported that pollock may stay over deep water in relatively cold years. For example, 1965-70 were thought to have been relatively warm years, and 1971-75 were thought to have been relatively cold years.

Pollock may be less susceptible to being harvested when they are over deeper water in cold years; additionally, their growth may be slower in cold years. These factors could cause reported catches to decrease in cold years and increase in warm years, possibly accounting for part of the trend of underprediction in 1965-70, which became less pronounced in 1971-75.

6) Changing catchability due to depletion of a more susceptible component of the pollock stock. If the eastern Bering Sea pollock population actually consists of two (or more) subpopulations, the depletion of the more susceptible stock might cause the observed trend (1972-80) of reported catches

becoming low relative to simulated catches. Okada (1979) reported a substantial pollock biomass over the Aleutian basin apparently consisting only of pollock more than about 5 yr old. If one stock of pollock has a greater tendency than another to migrate from the continental shelf to the Aleutian basin, where comparatively little fishing is done, the less migratory stock would presumably be more vulnerable to the fishery and might have become relatively depleted. Larkin (1977:4) briefly reviews this subject for other fish stocks.

7) Random errors in the CPUE index or reported catch data. The residuals graphed in Figure 5 show some apparently random departures from the general increasing (1964-69) and decreasing (1972-80) trend. These departures could be due in part to random errors in measuring the CPUE indices or reported catches. This is difficult to assess, however, since confidence intervals (or other measures of the amount of random variation in the CPUE indices or reported catches) were not published.

8) Propagated errors in the simulation. POL is a time-sequential model. The state of the system in one instant of simulated time is used in calculating the state of the system in the next instant of simulated time. Consequently, an error in one simulated year (for example, an incorrect value for the maximum fishing mortality rate, F) may have an effect on the state of the system during the next year, causing errors to be propagated through time. This also could cause serial correlation of errors.

3.2. Validity of Pollock Population Numbers, Age 1 and Older

Low (1979:table 7) estimated pollock population numbers exploited by the eastern Bering Sea fishery at ages 2-12 for the years 1970-78 using cohort analysis with catch data from 1973-78 (Low 1979:table 5). Smith (1981:table 33-3) estimated pollock population numbers at ages 1 and older in a 1.591×10^5 km^2 survey area in the eastern Bering Sea for the years 1973-78. His population estimates were based on estimates of nominal sampling effort, uncorrected for differences in effective fishing power between survey vessels or recruitment at age. The population estimates of Low and Smith are reproduced in Tables 8 and 9. The estimates of pollock population numbers from POL for 1 July 1970-78, under nonstationary conditions, are shown in Table 10.

The population estimates of Low (1979) and Smith (1981) were used to fit the stationary behavior of POL, but were not used to fit nonstationary behavior. However, there is an indirect connection between Low's estimates and the model estimates of pollock population numbers under nonstationary conditions because the total reported annual catches used in Low's estimates were also used in estimation of parameter q. This was the only parameter used to fit the nonstationary behavior of POL.

Low's values were assumed to apply to an effective area of 10^6 km^2 for comparisons with the model values. A logarithmic transformation was used prior to comparisons because graphical analysis indicated this stabilized the variance. The R^2 between logarithms of Low's values and logarithms of corresponding model values was 0.728, which indicated that qualitative similarities existed. However, Low's values had an influence on the choice of 72 model parameters. It was not possible to determine exactly how many df were used to fit POL. Since 99 data points were obtained from Low, 27 df were left after fitting POL, if it is assumed that one df was associated with each data point and that one df should be subtracted for each parameter

Table 8.--Number of walleye pollock in the eastern Bering Sea, 1970-78, estimated using virtual population analysis (Low 1979:table 7).

	Population size in millions of fish								
Age (year)	1970	1971	1972	1973	1974	1975	1976	1977	1978
2	11,382	10,019	4,502	5,572	15,951	10,704	11,087	9,622	7,261
3	7,363	7,629	6,716	3,018	3,229	8,143	6,603	7,062	5,523
4	4,112	4,935	5,114	4,502	1,411	1,222	2,827	3,027	3,495
5	2,863	2,757	3,308	3,428	1,687	678	617	953	1,131
6	1,289	1,919	1,848	2,218	1,280	771	400	321	317
7	330	864	1,287	1,239	791	663	416	226	143
8	66	221	579	862	443	406	348	219	125
9	46	44	148	388	298	192	219	164	109
10	8	31	30	100	134	97	98	93	80
11	8	6	21	20	44	47	43	39	38
12	4	6	4	14	11	12	26	17	14

Table 9.--Indices of age-class abundance of walleye pollock (Smith 1981:table 33-3). a/

Survey year	Age (year)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1973	756.9	518.2	146.0	193.4	99.4	34.4	91.5	117.8	18.9	17.9	4.51	-	0.401	0.072	-
1974	2,840.6	850.3	287.9	56.1	67.7	38.0	39.1	29.0	29.5	5.12	3.00	0.176	0.190	-	-
1975	758.4	402.4	614.2	108.0	24.6	27.5	14.7	14.2	7.98	5.99	0.52	0.594	0.009	-	-
1976	729.0	500.4	479.7	1,014.1	132.5	35.0	38.8	46.2	41.0	22.3	8.28	1.850	0.607	0.032	0.171
1977	2,241.9	630.2	145.8	245.3	231.9	72.0	29.8	23.7	23.6	13.1	11.9	3.200	0.491	0.180	-
1978	1,170.9	400.4	806.9	507.0	139.5	92.3	29.1	24.2	29.1	19.0	6.26	5.100	-	-	-

a/ Units = 10^6 individuals/(1.591 x 10^5 km^2). Indices based on estimates of nominal sampling effort, uncorrected for differences in effective fishing power, measured by National Marine Fisheries Service crab-groundfish research vessel surveys within a central area of the eastern Bering Sea during June to mid-August 1973-78.

Table 10.--Simulated pollock population numbers ($10^6/10^6$ km^2) on 1 July 1970-78 under nonstationary conditions.

Age (year)	1970	1971	1972	1973	1974
1	6,100	6,700	8,000	9,200	11,000
2	4,100	4,100	4,600	5,400	6,400
3	3,200	3,200	3,300	3,600	4,300
4	1,800	1,700	1,500	1,400	1,400
5	1,100	1,000	880	730	640
6	710	600	490	380	310
7	440	370	290	210	160
8	280	230	180	130	89
9	180	150	110	78	53
10	120	95	70	48	33
11	75	60	44	29	19
12	36	28	20	14	8.8
13	13	9.8	7.1	4.7	3.0
14	3.4	2.7	1.9	1.2	0.80
15	0.93	0.73	0.52	0.34	0.21
16	0.25	0.20	0.14	0.092	0.058
17	0.069	0.054	0.039	0.025	0.016
18	0.019	0.015	0.011		

Age (year)	1975	1976	1977	1978
1	9,100	7,200	5,800	5,600
2	7,400	6,600	5,500	4,500
3	5,000	5,900	5,300	4,400
4	1,900	2,500	3,100	2,800
5	700	760	910	1,300
6	290	330	380	460
7	140	140	160	190
8	74	66	68	83
9	41	35	33	34
10	24	19	17	16
11	14	11	9.1	8.3
12	6.3	4.8	3.8	3.3
13	2.1	1.6	1.3	1.0
14	0.56	0.40	0.31	0.26
15	0.15	0.11	0.081	0.064
16	0.039	0.028	0.021	0.017
17	0.011			
18				

influenced. Then an F-test (F=(92.87/98)/ (25.30/27)) indicates an approximate significance level of 49.1% for the correlation, which is not statistically significant.

Similarly, Smith's values were assumed to apply to an effective area of 1.591×10^5 km^2 (which was the area of the survey index area) in order to convert them for comparison with the model values. A logarithmic data transformation was used because graphical analysis indicated this stabilized the variance. The R^2 between logarithms of Smith's values and logarithms of corresponding model values was 0.833, indicating the existence of similarities. Smith's values had an influence on the choice of 26 model parameters. Assuming that one df was associated with each of the 80 data points from Smith, and conservatively assuming that 1 df should be subtracted for each of the 26 parameters influenced, implies that 54 df were left after fitting POL. An F-test (F=(112.1/79)/(18.67/54)) then indicates an approximate significance level of 99.9% for the correlation.

An analysis of variance (ANOVA) was performed on the logarithms of the ratios of Low's values to the model values. A similar ANOVA was performed on the logarithms of the ratios of Smith's values to the model values (the logarithmic transformation was used to stabilize the variance). The values were grouped according to 2-yr time periods (with the exception of 1970, since data from an odd number of years was analyzed) and according to pollock age-class. The results of these ANOVAs are summarized in Tables 11-14. Although R^2 values showed that the model values were similar to Low's or Smith's population values (and this similarity was statistically highly significant in the case of Smith's values), the results of the ANOVAs showed that there were

Table 11.--Analysis of variance of the base 10 logarithms of ratios of the walleye pollock population estimates of Low (1979:table 7) to corresponding model population estimates.

Source of variation	Sum of squares	df	Mean square	F ratio
Main effects	5.730	14	0.409	11.7a/
Age-class	1.566	10	0.157	4.48a/
Time period	4.164	4	1.041	29.8a/
Two-way interactions				
Age-class by time period	12.795	40	0.320	9.16a/
Explained	18.526	54	0.343	9.82a/
Residual	1.537	44	0.03493	
Total	20.063	98	0.205	

a/ Significant at 95% level.

Table 12.--Statistical significance of ratios of the pollock population numbers estimated by Low (1979:table 7) to simulated values.

Category	Number of values	Mean of logarithms[a]	95% joint confidence interval[b]
Grand mean	99	0.23[c]	(0.17, 0.29)
Age-class (year)			
2	9	0.23[c]	(0.03, 0.43)
3	9	0.15	(-0.05, 0.35)
4	9	0.20[c]	(0.01, 0.40)
5	9	0.26[c]	(0.07, 0.46)
6	9	0.33[c]	(0.13, 0.53)
7	9	0.39[c]	(0.19, 0.59)
8	9	0.39[c]	(0.20, 0.59)
9	9	0.35[c]	(0.15, 0.54)
10	9	0.18[c]	(-0.01, 0.38)
11	9	0.03	(-0.16, 0.23)
12	9	0.01	(-0.19, 0.21)
Time period			
1970	11	-0.24[c]	(-0.42, -0.06)
1971-72	22	0.08	(-0.05, 0.20)
1973-74	22	0.40[c]	(0.28, 0.53)
1975-76	22	0.38[c]	(0.26, 0.51)
1977-78	22	0.29[c]	(0.16, 0.42)

a/ Category mean of base 10 logarithms of the ratios of Low's values to the corresponding simulated values.

b/ Calculated using Bonferroni's inequality (Bickel and Doksum 1977:162) to give an overall confidence of at least 95% for the means of logarithms.

c/ Statistically different from zero at approximately the 95% level.

Table 13.--Analysis of variance of the base 10 logarithms of the ratios of walleye pollock population estimates of Smith (1981:table 33-3) to corresponding model population estimates.

Source of variation	Sum of squares	df	Mean square	F ratio
Main effects	8.988	16	0.562	3.69[a]
Age-class	7.191	14	0.514	3.38[a]
Time period	1.791	2	0.896	5.89[a]
Two-way interactions				
Age-class by time period	3.727	26	0.143	0.943
Explained	12.715	42	0.303	1.99[a]
Residual	5.628	37	0.1521	
Total	18.343	79	0.232	

a/ Significant at 95% level.

Table 14.--Statistical significance of ratios of the pollock population numbers estimated by Smith (1981:table 33-3) to simulated values.

Category	Number of values	Mean of logarithms[a]	95% joint confidence interval[b]
Grand mean	80	0.06	(-0.08, 0.20)
Age-class (year)			
1	6	0.00	(-0.52, 0.51)
2	6	-0.25	(-0.76, 0.27)
3	6	-0.34	(-0.86, 0.17)
4	6	-0.16	(-0.67, 0.36)
5	6	-0.14	(-0.65, 0.38)
6	6	-0.10	(-0.61, 0.41)
7	6	0.12	(-0.39, 0.63)
8	6	0.40	(-0.11, 0.91)
9	6	0.51[c]	(0.00, 1.02)
10	6	0.49[c]	(-0.02, 1.01)
11	6	0.27	(-0.25, 0.78)
12	5	0.19	(-0.37, 0.76)
13	5	-0.29	(-0.85, 0.27)
14	3	-0.06	(-0.79, 0.67)
15	1	1.00	(-0.26, 2.26)
Time period			
1973-74	26	-0.07	(-0.32, 0.18)
1975-76	28	-0.01	(-0.25, 0.23)
1977-78	26	0.28[c]	(0.03, 0.52)

a/ Category mean of base 10 logarithms of the ratios of Smith's values to the corresponding simulated values.

b/ Calculated using Bonferroni's inequality (Bickel and Doksum 1977:162) to give an overall confidence of at least 95% for the means of logarithms.

c/ Statistically different from zero at approximately the 95% level.

also statistically significant differences attributable to 2-yr time periods and pollock age-class. In the future it may be fruitful to explore the causes of these differences, possibly leading to improved model calibration.

From the confidence intervals presented in Table 12, the following specific differences between Low's estimates and the estimates from POL can be noted.

1) The grand mean of all the logarithms was significantly greater than zero at the 95% level, indicating that overall, Low's estimates were greater than those from POL.
2) On the average, Low's population estimates for age-classes 2 and 4-10 (model cohorts 3 and 5-11) were greater than those from POL, at a significance level of about 95%.
3) On the average, Low's population estimates were less for 1970 and greater for 1973-78 than those from POL, at a significance level of 95%.

From the confidence intervals presented in Table 14, the following can be noted about differences between Smith's estimates and the estimates from POL.

1) The grand mean of all the logarithms was not significantly different from zero at the 95% level, indicating that overall, Smith's estimates were not significantly different from those of POL.
2) On the average, Smith's population estimates for age-classes 9-10 (cohorts 10-11) were greater than those from POL, at a significance level of about 95%.
3) On the average, Smith's population estimates for 1977-78 were greater than those from POL, at a significance level of 95%.

3.3. Validity of Pollock Lengths

3.3.1. Pollock Lengths, Cohort 1

Pollock lengths in POL were intended to represent the fork lengths (FL) of living pollock. Fork length is measured from the tip of the longest jaw or end of snout, whichever is terminal (mouth closed), to the center (vertex) of the tail fork (Miller and Lea 1972:fig. 2). However, the youngest stages of pollock have a rounded tail (Gorbunova 1954:fig. 20). In this study, the term "fork length," when used for these stages of pollock, refers to length measured to the tip (middle) of the tail.

Most available data on the lengths of the earliest stages of pollock were presented in the source publications in terms of standard length (SL). Standard length is measured in systematics work from the end of the upper jaw or snout, to the end of the hypural bone (Miller and Lea 1972:fig. 2). In this study, standard lengths were calculated (unless noted otherwise) from simulated fork lengths by means of the relationship

$$SL = \begin{cases} 0.974 \times FL, \text{ if } FL \leq 5.5 \\ (0.9938 - 0.00359 \times FL) \times FL, \text{ if } 5.5 < FL < 20.0 \\ 0.922 \times FL, \text{ if } FL \geq 20.0 \end{cases} \qquad (3)$$

where FL and SL are measured in millimeters. This relationship is continuous. It was derived using subjective graphical analysis of the functional relationship of SL/FL to FL, using data measured from diagrams of pollock up to 40 mm FL in Gorbunova (1954:fig. 20). It is also reasonable for pollock > 100 mm FL (Yamaguchi and Takahashi 1972: eq. 17 and fig. 12).

Much available data on the lengths of the early life history stages of pollock were measured using pollock preserved in formaldehyde. Haryu (1980:126-127), citing various authors, stated that the shrinkage of length of fish larvae preserved in 4% formalin was 1-10%. In this study, 5% shrinkage was assumed for the standard length of pollock preserved in any concentration of formaldehyde solution.

Figure 7 compares data on the standard length of cohort 1 pollock preserved in formalin (Cooney et al. 1979:fig. 19), with equivalent simulated standard lengths. Table 15 lists the simulation data used in Figure 7. All the simulated values are within or close to the range of measured values (see also Nishiyama 1981:table 5), so POL apparently gives useful predictions of cohort 1 lengths. However, since all of the simulated values are on the low side, analysis based on more detailed data might also show statistically significant differences.

The goodness-of-fit of the nonstationary cohort 1 lengths to actual data (Figure 7) is a result of the fact that the same data were used to fit the stationary cohort 1 lengths (Figure 2), and there was almost no change between the stationary and nonstationary lengths for this cohort.

3.3.2. Pollock Lengths, Cohorts 2-16

Figure 8 shows a graph of simulated lengths together with the minimums, medians, and maximums of pollock lengths measured in the eastern Bering Sea during 22 May-24 August 1979. Table 16 gives the 1979 pollock length data

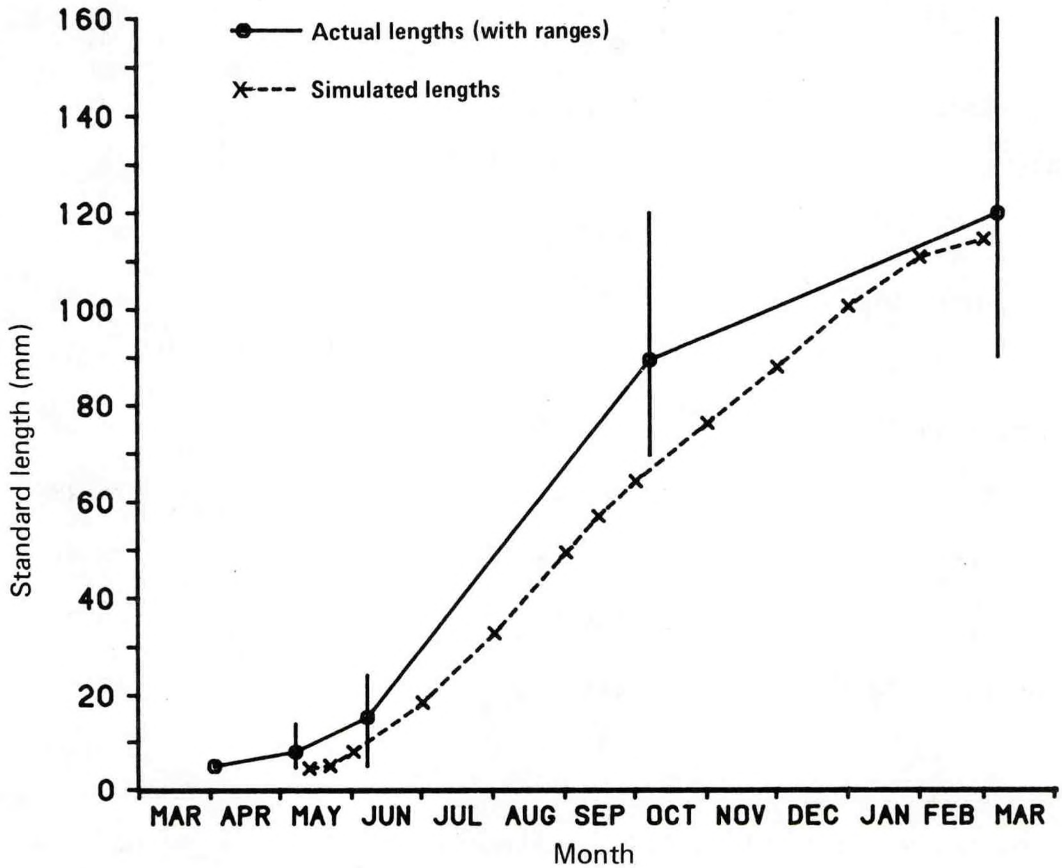

Figure 7.--Simulated 1977-78 growth in length of walleye pollock <1-yr-old compared with actual lengths (Cooney et al. 1979:fig. 19). See Table 15.

Table 15.--Simulated lengths of cohort-1 pollock.

Simulated date	Simulated fork length (mm)	Equivalent standard length[a/] (mm)
13 May 1977	4.66	4.31
22 May 1977	5.22	4.83
1 June 1977	8.55	7.82
1 July 1977	21.10	18.48
1 August 1977	37.44	32.79
1 September 1977	56.46	49.45
15 September 1977	65.08	57.00
1 October 1977	73.37	64.26
1 November 1977	87.10	76.29
1 December 1977	100.48	88.01
1 January 1978	115.00	100.7
1 February 1978	126.57	110.9
1 March 1978	130.88	114.6

a/ Computed using eq. (3), and assuming 5% shrinkage due to effects of preservation in formaldehyde.

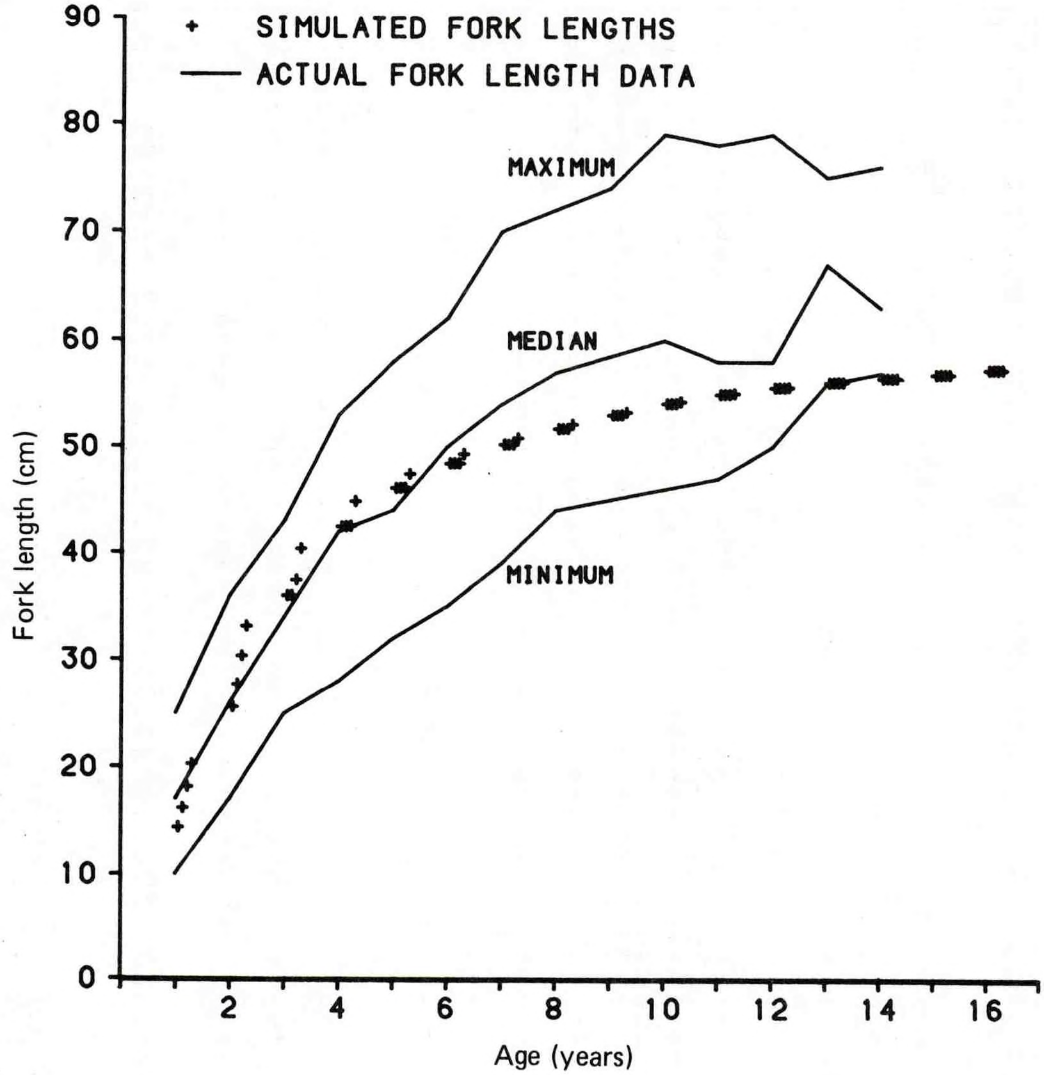

Figure 8.--Comparison of actual and simulated adult walleye pollock length-at-age data. Actual data are from Table 17, simulated data are from Table 18.

Table 16.--Number of walleye pollock of given age and fork length (eastern Bering Sea survey data, 22 May-24 August 1979).

LENGTH (cm)	AGE (year) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL
10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
11	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
12	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19
13	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32
14	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36
15	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49
16	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53
17	58	2	0	0	0	0	0	0	0	0	0	0	0	0	0	60
18	34	9	0	0	0	0	0	0	0	0	0	0	0	0	0	43
19	28	10	0	0	0	0	0	0	0	0	0	0	0	0	0	38
20	28	45	0	0	0	0	0	0	0	0	0	0	0	0	0	73
21	19	50	0	0	0	0	0	0	0	0	0	0	0	0	0	69
22	13	46	0	0	0	0	0	0	0	0	0	0	0	0	0	59
23	15	49	0	0	0	0	0	0	0	0	0	0	0	0	0	64
24	4	52	0	0	0	0	0	0	0	0	0	0	0	0	0	56
25	1	51	4	0	0	0	0	0	0	0	0	0	0	0	0	56
26	0	69	9	0	0	0	0	0	0	0	0	0	0	0	0	78
27	0	50	13	0	0	0	0	0	0	0	0	0	0	0	0	63
28	0	41	19	3	0	0	0	0	0	0	0	0	0	0	0	63
29	0	43	22	1	0	0	0	0	0	0	0	0	0	0	0	66
30	0	42	23	1	0	0	0	0	0	0	0	0	0	0	0	66
31	0	34	28	2	0	0	0	0	0	0	0	0	0	0	0	64
32	0	30	35	4	2	0	0	0	0	0	0	0	0	0	0	71
33	0	24	44	7	0	0	0	0	0	0	0	0	0	0	0	75
34	0	11	42	13	2	0	0	0	0	0	0	0	0	0	0	68
35	0	4	37	11	8	1	0	0	0	0	0	0	0	0	0	61
36	0	1	33	13	10	2	0	0	0	0	0	0	0	0	0	59
37	0	0	38	17	12	1	0	0	0	0	0	0	0	0	0	68
38	0	0	30	23	16	2	0	0	0	0	0	0	0	0	0	71
39	0	0	30	22	13	2	1	0	0	0	0	0	0	0	0	68
40	0	0	25	37	13	3	1	0	0	0	0	0	0	0	0	79
41	0	0	17	30	18	10	0	0	0	0	0	0	0	0	0	75
42	0	0	5	34	24	12	1	0	0	0	0	0	0	0	0	76
43	0	0	2	34	28	11	1	0	0	0	0	0	0	0	0	76
44	0	0	0	33	29	19	4	2	0	0	0	0	0	0	0	87
45	0	0	0	29	25	14	5	2	2	0	0	0	0	0	0	77
46	0	0	0	27	27	14	6	1	3	2	0	0	0	0	0	80
47	0	0	0	20	21	13	13	2	4	2	1	0	0	0	0	76
48	0	0	0	23	16	17	9	5	7	4	2	0	0	0	0	83
49	0	0	0	4	21	24	13	5	6	4	3	0	0	0	0	80
50	0	0	0	9	12	20	16	2	8	4	3	3	0	0	0	77
51	0	0	0	4	8	18	19	12	10	9	3	4	0	0	0	87
52	0	0	0	2	8	23	22	9	4	7	5	3	0	0	0	83
53	0	0	0	1	7	20	21	9	8	9	2	1	0	0	0	78
54	0	0	0	0	1	17	27	9	6	4	3	0	0	0	1	68
55	0	0	0	0	1	9	19	20	5	6	7	2	0	0	0	69
56	0	0	0	0	4	9	11	10	9	6	5	1	1	0	0	56
57	0	0	0	0	2	12	15	11	17	7	4	4	1	1	0	74
58	0	0	0	0	2	10	12	5	10	1	4	1	1	1	0	47
59	0	0	0	0	0	3	8	14	11	6	5	0	1	0	0	48
60	0	0	0	0	0	4	15	9	14	5	4	0	0	0	0	51
61	0	0	0	0	0	2	13	10	8	10	2	1	0	0	0	46
62	0	0	0	0	0	2	10	7	11	7	5	0	0	0	0	42
63	0	0	0	0	0	0	5	6	11	10	5	2	0	2	0	41
64	0	0	0	0	0	0	4	11	4	6	1	2	0	1	0	29
65	0	0	0	0	0	0	9	7	11	10	2	0	0	0	0	39
66	0	0	0	0	0	0	2	4	8	6	1	0	0	0	0	21
67	0	0	0	0	0	0	4	5	4	5	3	0	2	0	0	23
68	0	0	0	0	0	0	3	3	3	5	5	1	0	0	0	20
69	0	0	0	0	0	0	3	0	5	3	1	2	1	0	0	15
70	0	0	0	0	0	0	1	3	4	1	0	3	1	0	0	13
71	0	0	0	0	0	0	0	2	3	2	2	1	0	0	0	10
72	0	0	0	0	0	0	0	2	1	2	0	2	1	1	0	9
73	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	3
74	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2
75	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	2
76	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	3
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
79	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	2
TOTAL	393	663	456	404	330	294	293	187	198	145	82	37	11	7	1	3501

used.[1/] Table 17 gives summary statistics calculated from the length data for each age category. Table 18 gives simulated lengths at the beginning of the month for June-September 1979, together with mean summer values.

The total sum of squares of the actual lengths about their overall mean was 778,565 (df=3,500). The residual sum of squares from a one-way ANOVA (with age being the independent variable) was 88,060.7 (df=3,486). The residual sum of squares about the simulated summer means for each age category was 127,329 (df=3,501). The R^2 of the simulated summer means with the actual data was 0.836. Using an F-test, this had an approximate significance level of more than 99.9%. So POL predicted much of the variation in pollock lengths during the summer of 1979, for age-classes 1-15.

However, using another F-test, the significance level of the reduction of the sum of squares about the simulated summer means compared to the residual sum of squares from the one-way ANOVA with age as the independent variable was also more than 99.9%, indicating that there were aspects of the variation in pollock lengths attributable to age-class which POL did not perfectly predict. In particular, comparison of the range of simulated values in Table 18 with the joint confidence intervals given in Table 17 indicates that age-classes 3-5 (cohorts 4-6) were longer than would be expected from the actual data and age-classes 7-13 (cohorts 8-14) were shorter than expected. Nonetheless, all simulated values (with the insignificant exceptions of age-classes 14 and 15) were within the range of values actually measured.

1/ Data on file in a data base at the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Boulevard East, Seattle, WA 98112.

Table 17.--Walleye pollock length statistics determined from Table 16.

Age (year)	Number	Minimum length (cm)	Median length (cm)	Maximum length (cm)	Mean length (cm)	Standard deviation (cm)	95% joint[a] confidence intervals (cm)
1	393	10	17.0	25	16.832	3.002	(16.4, 17.3)
2	663	17	26.0	36	25.872	4.082	(25.4, 26.3)
3	456	25	34.0	43	34.221	4.062	(33.7, 34.8)
4	404	28	42.0	53	41.757	4.646	(41.1, 42.4)
5	330	32	44.0	58	44.200	5.016	(43.4, 45.0)
6	294	35	50.0	62	49.442	5.424	(48.5, 50.4)
7	293	39	54.0	70	54.741	5.945	(53.7, 55.8)
8	187	44	57.0	72	57.588	6.088	(56.3, 58.9)
9	198	45	58.5	74	58.318	6.572	(56.9, 59.7)
10	145	46	60.0	79	59.062	6.916	(57.4, 60.8)
11	82	47	58.0	78	59.049	7.080	(56.7, 61.4)
12	37	50	58.0	79	61.189	9.018	(56.5, 65.8)
13	11	56	67.0	75	65.818	7.083	(57.7, 74.0)
14	7	57	63.0	76	64.714	6.969	(52.4, 77.0)
15	1	54	54.0	54	54.000	-	-
Combined	3,501	10	41.0	79	40.166	14.915	-

a/ Calculated assuming 15 confidence intervals would be determined. The estimate of standard deviation for each individual age category was used. Each data value was assumed independent of the others. Taken as individual confidence intervals, the intervals are 100 x $(.95)^{(1/15)}$% confidence intervals.

Table 18.--Simulated walleye pollock lengths (ages 1-16) for four simulated dates in 1979.

Age (year)	Fork length (cm) 1 June	1 July	1 August	1 September	Summer mean a/
1	14.3	16.1	18.1	20.2	17.2
2	25.6	27.7	30.3	33.1	29.2
3	36.0	36.0	37.4	40.4	37.4
4	42.5	42.5	42.5	44.8	43.1
5	46.1	46.1	46.1	47.4	46.4
6	48.5	48.5	48.5	49.3	48.7
7	50.2	50.2	50.2	50.8	50.4
8	51.7	51.7	51.7	52.1	51.8
9	53.0	53.0	53.0	53.3	53.1
10	54.1	54.1	54.1	54.3	54.2
11	55.0	55.0	55.0	55.1	55.0
12	55.6	55.6	55.6	55.7	55.6
13	56.1	56.1	56.1	56.2	56.1
14	56.5	56.5	56.5	56.5	56.5
15	56.9	56.9	56.9	56.9	56.9
16	57.3	57.3	57.3	57.3	57.3

a/ Calculated as the unweighted mean of the values shown in the previous four columns.

3.4. Validity of Pollock Weights

Whenever possible, the simulated age-weight relationship was compared with actual age-weight data measured for freshly caught pollock. Such data were unavailable for the youngest age-classes; instead, the simulated length-weight relationship was compared with length-weight data measured for pollock preserved in formaldehyde or by freezing. Haryu (1980:126-127), citing various authors, stated that the weight of fish larvae is reduced by about 20% after preservation in 4% formalin. Consequently, simulated weights were multiplied by 0.8 before comparisons with weights of pollock preserved in any concentration of formaldehyde. It was assumed that frozen pollock in this study experienced no loss in weight or length.

3.4.1. Pollock Weights, Cohorts 1-3

Haryu (1980) and P. Walline (School of Oceanography, University of Washington, Seattle, WA 98195; pers. commun., 1981) determined length-weight relationships for pollock in the size range 0.5-20.7 cm SL. As discussed below, from their data it appeared that the length-weight relationship of simulated small pollock (about 0.6-3.9 cm SL or approximately 0.6-4.5 cm FL) was unrealistic in POL, but became much closer to actual data somewhere in the range 3.9-5.7 cm SL (approximately 4.5-6.2 cm FL).

3.4.1.1. <u>Weights of Pollock of about 0.5-3.9 cm Standard Length</u>--Haryu (1980) determined the length-weight relationship of larval and postlarval pollock caught in the Bering Sea in June to August, 1970-74, which had been preserved in a 5-10% formaldehyde solution. After preservation, the pollock measured

5-39 mm SL. Figure 9 compares the length-weight relationship determined by Haryu with a length-weight relationship calculated from values produced by POL for the simulated time period 13 May-31 August 1972. The simulated values used are shown in Table 19. The comparison between the model values (originally calculated in terms of fork length and intended to represent living pollock) and Haryu's values is only approximate because the exact changes from the live length-weight relationship, due to handling after capture and preservation in formaldehyde, were not determined. Bailey (1982:593) found large changes in lengths and weights of larval Pacific hake (Merluccius productus) due to handling time and preservation; larval pollock may be similarly affected.

The difference between Haryu's length-weight relationship and the simulated length-weight relationship appears to be statistically significant despite the above uncertainties. Out of the 106 pollock measured by Haryu, all but the smallest one weighed more than expected using the length-weight relationship calculated from the simulated values. The maximum deviation of Haryu's regression lines from a regression line calculated for simulated pollock about 4.8-49.3 mm SL occurred at about 7.8 mm SL. After adjustments for the effects of preservation in formaldehyde, a 7.8 mm SL pollock measured by Haryu would be expected to weigh about 3.1 times the simulated weight of a pollock of comparable length, and a 39 mm SL pollock would be expected to weigh about 1.9 times the simulated weight.

In another sense, however, the difference between Haryu's data and the simulated values was not very great. Young pollock grow very rapidly, and a simulated pollock of given length increased its weight in only 1-2 simulated

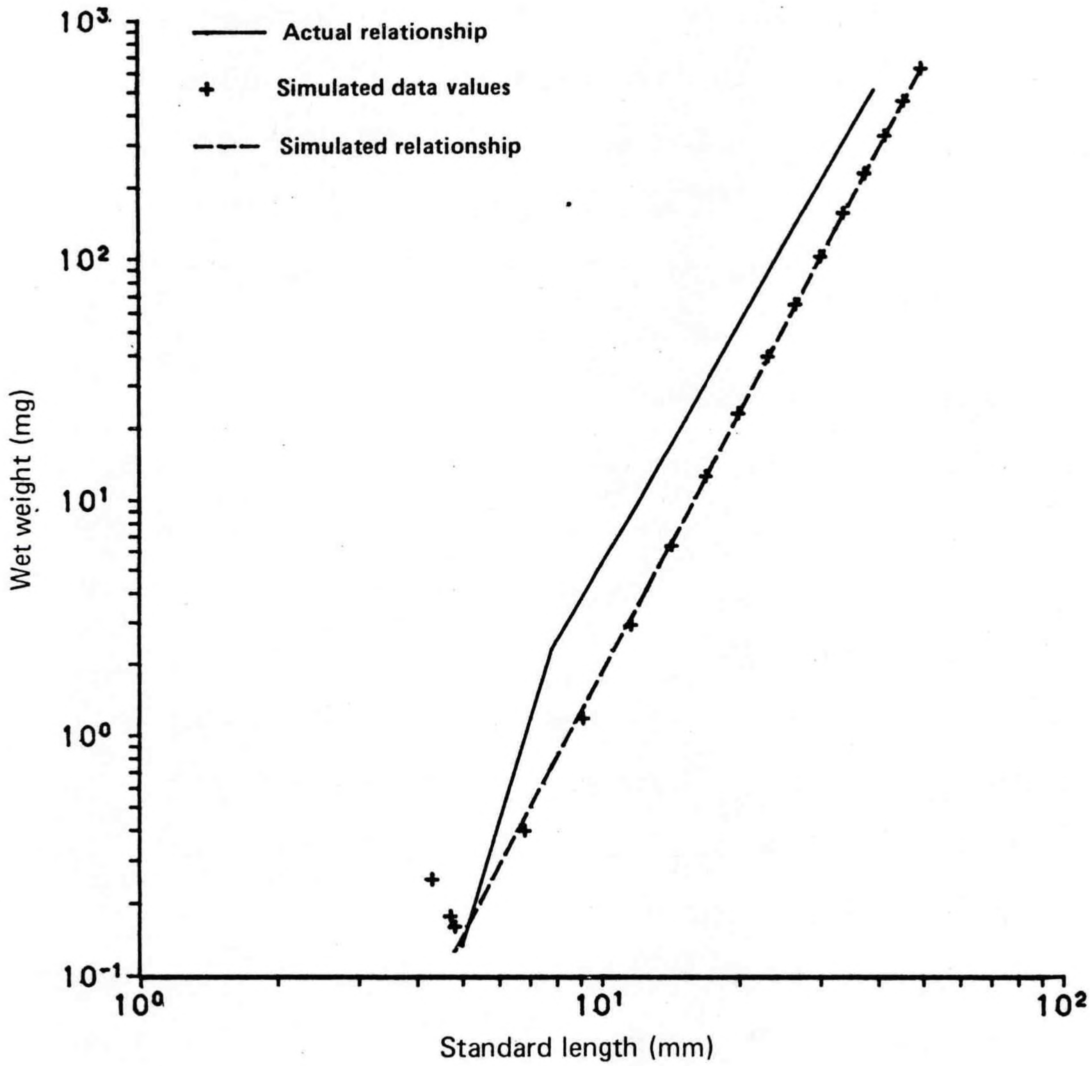

Figure 9.--Comparison of an actual length-weight relationship for larval walleye pollock (Haryu 1980: fig. 5) with a relationship determined from simulated values. The actual relationship was determined from pollock captured June to August 1970-74 and preserved in formaldehyde. Simulated data values were for 13 May-31 August 1972.

Table 19.--Lengths and weights of simulated pollock (cohort 1) during the time period 13 May-31 August 1972.

Simulated date	Fork length (mm)	Wet weight (mg)	Adjusted standard length[a] (mm)	Adjusted weight[a] (mg)
13 May	4.66	0.314	4.31	0.251
20	5.10	0.221	4.72	0.177
22	5.22	0.200	4.83	0.160
28	7.43	0.497	6.83	0.397
4 June	10.0	1.47	9.13	1.18
11	12.9	3.64	11.6	2.91
19	15.9	7.90	14.2	6.32
26	19.2	15.6	16.9	12.5
3 July	22.7	28.5	19.9	22.8
11	26.4	49.0	23.1	39.2
18	30.2	80.3	26.4	64.2
25	34.2	126	29.9	101
1 August	38.3	191	33.5	153
9	42.6	281	37.3	225
16	47.0	403	41.2	323
23	51.6	565	45.2	452
31	56.3	774	49.3	620

a/ Intended to represent standard lengths and weights of walleye pollock after preservation in 5-10% formaldehyde. Adjusted standard length was calculated using eq. (3); 5% shrinkage due to effects of preservation was also assumed. Adjusted weight was calculated assuming 20% shrinkage due to effects of preservation.

weeks to that previously expected from Haryu's length-weight relationship. However, because the length of the simulated pollock also increased in that time period, its weight still remained less than expected from Haryu's relationship.

3.4.1.2. Weights of Pollock of 5.7-20.7 cm Standard Length--P. Walline (School of Oceanography, University of Washington, Seattle, WA 98195; pers. commun., 1981) measured the weights and standard lengths of juvenile pollock from the Bering Sea which had been preserved by freezing. The pollock used in this analysis were caught 16 July-5 August 1978 (208 specimens), and 16 July 1979 (9 specimens). When necessary, pollock fork lengths (cm) were converted to standard lengths (cm) using the formula

$$SL = 0.9220 \times FL - 0.03251, \quad (4)$$

calculated by Yamaguchi and Takahashi (1972: eq. 17). This formula seemed reasonable for pollock down to about 2 cm FL (Gorbunova 1954:fig. 20). The pollock used in the analysis were 5.7-20.7 cm SL (about 6.2-22.5 cm FL). Although ages were not measured, Table 17 indicates that these pollock probably were in age-classes 0, 1, and 2 yr (cohorts 1, 2, and 3).

Figure 10 shows a log-log graph of Walline's values. Figure 11 shows 95% confidence belts calculated for the linear least squares regression line on these values using the methods of Snedecor and Cochran (1967: sections 6.11-6.12). The upper and lower boundary of a confidence belt for an individual or population consisted of the set of all points which were the upper or lower boundary of a 95% confidence interval for the "true" expected value of the dependent variable for an individual or population of given length. In

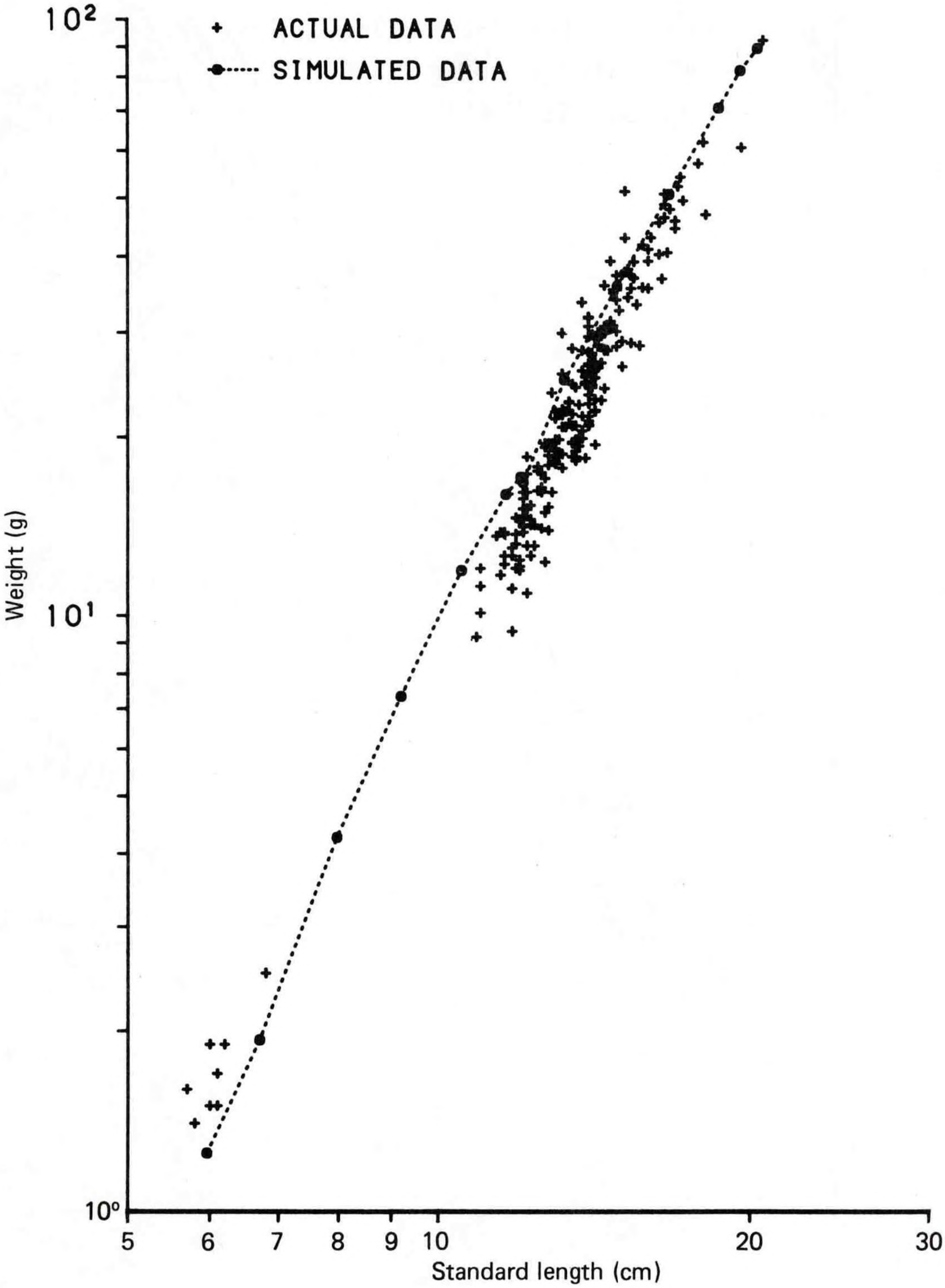

Figure 10.--Comparison of actual log-log length-weight data for juvenile walleye pollock with simulated values.

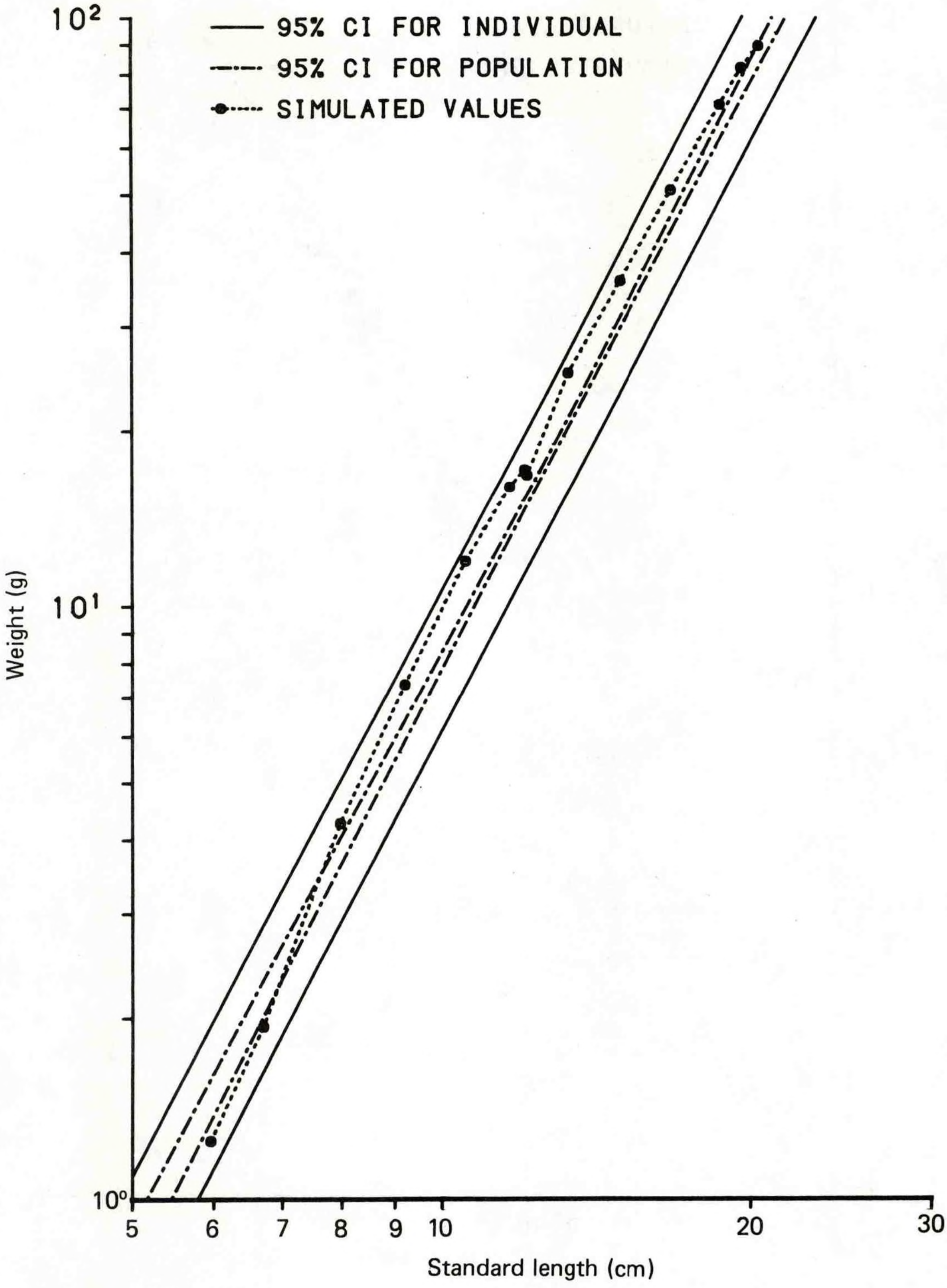

Figure 11.--Comparison of simulated log-log length-weight data for juvenile walleye pollock with actual 95% confidence intervals (CI) (called confidence belts by Snedecor and Cochran (1967: sections 6.11-6.12)).

addition, both figures show the comparable values from the model simulated for 1 February 1978 to 1 January 1979. The comparison of these model values with Walline's values is only suggestive, because the model values were taken from throughout an entire simulated year, but Walline's values were measured during a short 3-wk time period in 1978 and 1979. The model values were entirely within the 95% confidence band for individual pollock, which suggested the model accurately accounted for much of the variation of length and weight in this size range. However, only one model data point was inside the 95% confidence band for the population means, indicating that there was still predictable variation unaccounted for by the model. Walline's values are shown in Table 20, and a summary table for the least squares linear regression on the logarithms of these values is shown in Table 21. The model values together with the 95% confidence intervals calculated from the linear regression are shown in Table 22. A nonlogarithmic graph of Walline's values and the model values is shown in Figure 12.

3.4.2 Pollock Weights, Cohorts 3-11

Pollock lengths and weights were measured during a 1979 eastern Bering Sea trawl survey conducted by the National Marine Fisheries Service.[2/] These data were selected because they were measured at a later date than any data used in fitting the model, and therefore could be used for predictive validation.

2/ Data on file in a data base at the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Boulevard East, Seattle, WA 98112.

Table 20.--Standard lengths (SL) and weights (W) of juvenile walleye pollock preserved by freezing, from different trawl hauls made in the Bering Sea (P. Walline, School of Oceanography, University of Washington, Seattle, WA 98195; pers. commun., 1981).

16 July 1978 N = 30		2 August 1978 N = 38		3 August 1978 N = 27		4 August 1978 N = 34		5 August 1978 N = 25		5 August 1978 N = 25		5 August 1978 N = 29		16 July 1979 N = 9	
SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)	SL (cm)	W (g)
11.0	11.2	11.5	11.7	12.1	13.8	11.5	13.8	11.0	12.0	10.9	9.2	5.7	1.6	12.6	17.38
11.6	12.2	12.0	12.1	13.5	24.6	11.6	13.7	11.6	12.6	11.0	10.1	5.8	1.4	13.3	22.12
11.8	11.1	12.0	12.4	13.6	18.5	11.7	16.0	11.8	9.4	11.4	13.6	6.0	1.5	14.1	24.31
11.8	13.0	12.1	15.7	13.8	25.9	12.2	17.3	12.0	11.9	11.6	13.8	6.0	1.9	14.1	24.54
11.9	13.2	12.2	15.1	13.9	25.3	12.3	15.3	12.2	16.1	11.8	12.6	6.1	1.5	14.1	25.57
11.9	13.7	12.3	12.6	14.2	29.3	12.8	15.2	12.4	14.2	11.9	12.0	6.1	1.7	14.2	25.20
11.9	14.6	12.4	13.1	14.3	30.0	13.0	22.1	12.5	17.5	12.1	14.7	6.2	1.9	14.3	28.46
12.0	14.4	12.5	17.8	14.5	35.8	13.4	22.9	12.6	14.0	12.1	15.1	6.8	2.5	14.7	30.85
12.1	14.1	12.7	12.3	14.8	35.2	13.5	28.2	12.7	17.0	12.2	10.9	12.1	16.1	14.9	28.40
12.1	14.7	12.7	14.9	14.9	33.9	13.8	28.0	12.8	19.5	12.2	13.1	12.2	18.5		
12.5	16.2	12.7	19.2	14.9	37.2	13.9	24.6	13.0	21.5	12.3	14.2	12.9	23.8		
12.6	16.1	12.9	16.1	15.3	34.2	13.9	24.7	13.4	22.2	12.3	14.5	13.2	25.6		
12.6	16.2	13.1	19.8	15.3	38.1	14.0	23.6	13.4	23.0	12.8	18.6	13.2	29.9		
12.6	16.4	13.2	20.8	16.0	35.4	14.0	24.5	13.5	19.5	13.2	18.7	13.5	19.6		
12.7	19.5	13.2	21.8	16.0	39.3	14.0	26.4	13.6	18.2	13.5	18.5	13.5	21.9		
12.8	13.9	13.2	22.3	16.4	45.5	14.0	26.6	13.6	20.9	13.6	19.8	13.8	33.6		
12.8	17.9	13.3	20.8	16.5	36.7	14.1	25.9	13.6	24.3	13.7	19.9	14.0	27.8		
12.9	19.2	13.5	20.9	16.6	46.4	14.1	27.5	14.0	21.7	14.0	20.9	14.0	29.5		
13.0	18.0	13.6	18.9	17.0	44.5	14.2	22.2	14.1	25.5	14.1	27.7	14.0	30.7		
13.0	18.2	13.7	22.7	17.0	45.8	14.2	22.2	14.2	23.2	14.4	23.1	14.0	31.7		
13.0	18.5	13.8	19.9	17.1	52.3	14.3	26.2	14.2	26.8	15.0	32.6	14.0	31.8		
13.0	19.1	13.8	20.5	17.2	54.2	14.3	28.5	14.7	30.4	15.1	37.3	14.7	39.3		
13.0	19.8	13.8	21.7	17.3	49.5	14.4	29.9	15.1	26.3	15.2	37.7	15.1	29.0		
13.1	18.7	13.9	18.4	17.9	57.1	14.5	28.0	15.4	28.8	15.8	35.5	15.2	42.9		
13.2	17.7	13.9	24.8	18.1	62.0	14.5	28.1	16.4	40.3	16.6	48.8	15.2	51.3		
13.4	21.1	14.0	21.0	18.2	46.9	14.5	29.9					15.5	39.2		
13.7	19.3	14.0	21.3	19.7	60.8	14.6	28.0					16.0	41.1		
14.3	28.6	14.0	22.8			14.7	31.3					16.1	43.0		
14.5	24.2	14.2	19.4			14.9	30.1					16.6	50.8		
14.8	30.8	14.2	22.1			15.4	35.4								
		14.4	26.7			15.4	37.2								
		14.4	29.6			15.5	36.8								
		14.5	30.7			15.6	33.3								
		14.8	34.8			15.8	41.8								
		15.7	28.5												
		16.7	40.6												
		16.8	47.9												
		20.7	92.3												

Table 21.--Analysis of variance for the length-weight relationship of juvenile pollock, resulting from a least squares linear regression of logarithms of pollock weights (W) on logarithms of pollock standard lengths (SL) determined from Table 20.

Source	df	Sums of squares	Mean square	F statistic
Regression	1	16.04066	16.04066	4,448[a]
Residual	215	0.77543	0.0036067	
Total	216	16.81609		

Regression equation estimated: $\log_{10} W = b_o + b_1 \times \log_{10} SL$

Coefficient	Estimated value	Standard deviation	Student's t ratio
b_o	-2.40036	0.05596	-42.9[a]
b_1	3.30744	0.04959	66.7[a]

Correlation coefficient = 0.97667

Standard deviation of $\log_{10} W$ on $\log_{10} SL$ = 0.060055

Mean of $\log_{10} SL$ = 1.1253

Mean of $\log_{10} W$ = 1.3214

a/ Significant at the 95% level.

Table 22.--Comparison of simulated length-weight data for juvenile pollock with confidence intervals determined from actual data.

Simulated date	Simulated fork length (cm)	Simulated[a/] standard length, SL (cm)	Simulated weight, W (g)	$\log_{10}SL$	$\log_{10}W$	95% confidence intervals (CI) from actual data[b/]	
						individual CI of $\log_{10}W$	population CI of $\log_{10}W$
15 September 1978	6.5	6.0	1.25	0.775	0.096	(0.04, 0.29)	(0.13, 0.20)
1 October 1978	7.3	6.7	1.93	0.826	0.29	(0.21, 0.46)	(0.30, 0.36)
1 November 1978	8.7	8.0	4.26	0.901	0.63	(0.46, 0.70)	(0.56, 0.60)
1 December 1978	10.0	9.2	7.35	0.964	0.87	(0.67, 0.91)	(0.77, 0.81)
1 January 1979	11.5	10.5	11.9	1.023	1.08	(0.86, 1.10)	(0.97, 1.00)
1 February 1978	12.7	11.6	16.0	1.066	1.20	(1.01, 1.24)	(1.11, 1.13)
1 March 1978	13.1	12.0	17.1	1.080	1.23	(1.05, 1.29)	(1.16, 1.18)
1 April 1978	13.2	12.1	16.7	1.083	1.22	(1.06, 1.30)	(1.17, 1.19)
1 June 1978	14.4	13.3	25.0	1.123	1.40	(1.19, 1.43)	(1.31, 1.32)
1 July 1978	16.2	14.9	35.7	1.174	1.55	(1.36, 1.60)	(1.47, 1.49)
1 August 1978	18.2	16.8	50.8	1.224	1.71	(1.53, 1.77)	(1.64, 1.66)
1 September 1978	20.3	18.7	70.9	1.272	1.85	(1.69, 1.93)	(1.79, 1.82)
15 September 1978	21.4	19.7	82.1	1.294	1.91	(1.76, 2.00)	(1.86, 1.90)
1 October 1978	22.2	20.4	89.4	1.310	1.95	(1.81, 2.05)	(1.91, 1.95)

a/ Estimated value for pollock of the given fork length.

b/ Confidence intervals for $\log_{10}W$ were predicted for the given $\log_{10}SL$ using the regression equation in Table 21 under the assumption of normality. An individual confidence interval (CI) is valid for an individual pollock of length SL. A population CI is valid for the population mean of $\log_{10}W$ for all pollock of length SL.

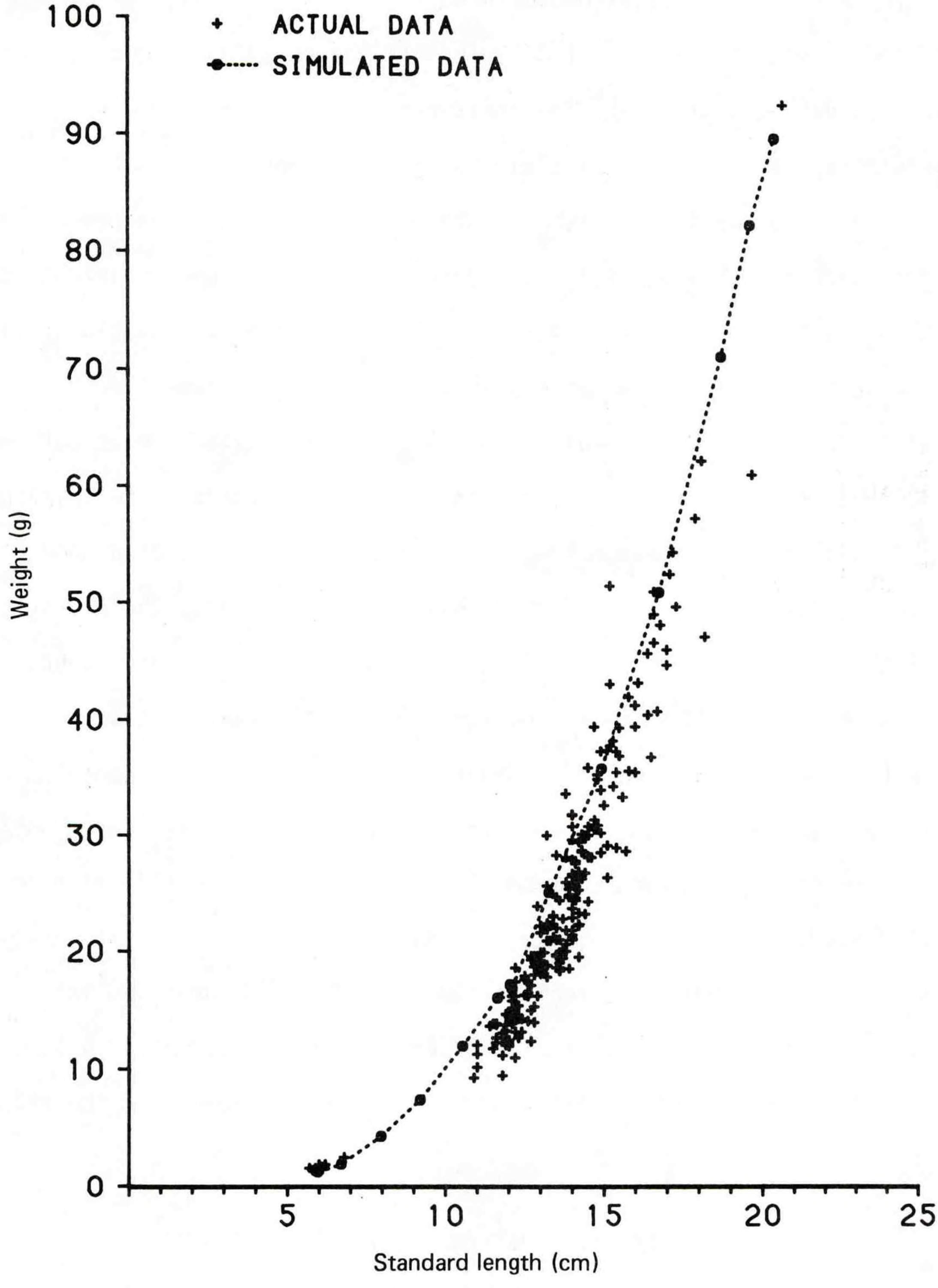

Figure 12.--Comparison of simulated and actual length-weight data for juvenile walleye pollock.

Table 23 lists the actual measured data and Table 24 gives simulated weights and lengths for 1 June, 1 July, and 1 August 1979. Figures 13 and 14 compare this data graphically. The total sum of squares of the actual weights about their overall mean was 2.1169×10^7 g^2 (df=58), their residual sum of squares from a two-way ANOVA (with age and nearest month of measurement being the independent variables) was 6.5133×10^6 g^2 (df=43), and their residual sum of squares about the simulated weight for the given age-class on the simulated date (1 June to 1 August) nearest the actual date of measurement was 1.4262×10^7 g^2 (df=59). The R^2 of the simulated weights with the actual data was 0.326, which, using an F-test, had an approximate significance level of 94.1%. This indicated a reasonable probability that POL predicted some of the variation in pollock weights. However, using another F-test, the significance level of the reduction in the sum of squares about the simulated weights compared with the residual sum of squares from the two-way ANOVA was approximately 94.5%. This indicates that there was also a reasonable probability that some predictable aspects of variation in weight attributable mainly to age-class were not predicted by POL (variations attributable to month of measurement were statistically insignificant in the actual data). The analysis of variance table for the two-way ANOVA is reproduced in Table 25. From Figure 13 it appears that on the average simulated pollock about 7 yr and older (model cohort 8 and older) weighed less than the measured pollock.

3.5. Validity of the Fraction Mature in Each Pollock Cohort

The fraction of a given pollock cohort of given length and sex which was considered to be mature enough to breed was forced to be realistic by use of

Table 23.--Age, weight, and length measurements for adult walleye pollock (eastern Bering Sea survey data, 1979).

Date caught	Latitude	Longitude	Age (year)	Weight (g)	Fork length (cm)
22 May	55°10'N	166°5'W	2	300	26
			2	300	28
			3	400	32
			3	500	37
			3	500	38
			3	600	41
			4	600	45
			4	700	44
			4	700	45
			4	800	45
			4	800	46
			4	900	47
			4	900	48
			4	900	48
			4	900	50
			5	600	43
			5	700	44
			5	1,100	50
			6	1,000	51
			7	800	46
			7	800	48
			7	1,000	51
			7	1,000	53
			8	1,000	51
17 July	60°30'N	175°0'W	2	485	20
			2	560	21
			2	595	22
			2	610	23
			4	1,000	48
			6	1,100	51
			6	1,350	55
			6	1,400	56
			7	800	47
			7	1,300	52
			7	2,350	65
			8	1,150	53
			8	1,600	58
			8	1,800	60
			9	950	47
			9	1,400	53
			9	1,900	59
			9	2,300	66
			9	3,100	71
			10	1,000	52
			10	1,200	54
			10	1,650	59
			10	2,100	66
20 July	61°10'N	178°0'W	2	71	21
			2	75	24
			2	130	27
			3	178	28
			4	346	36
			4	463	39
			5	329	35
			5	341	37
			5	350	35
			5	375	36
			5	479	41
			6	412	38

Table 24.--Simulated 1979 age, weight, and length data for adult walleye pollock.

Simulated date	Age (year)	Weight (g)	Fork length (cm)
1 June	1	24.5	14.3
	2	136	25.6
	3	282	36.0
	4	421	42.5
	5	541	46.1
	6	645	48.5
	7	736	50.2
	8	823	51.7
	9	906	53.0
	10	980	54.1
	11	1,041	55.0
	12	1,087	55.6
	13	1,125	56.1
	14	1,154	56.5
	15	1,180	56.9
	16	1,200	57.3
1 July	1	35.0	16.1
	2	181	27.7
	3	344	36.0
	4	459	42.5
	5	566	46.1
	6	662	48.5
	7	747	50.2
	8	830	51.7
	9	908	53.0
	10	980	54.1
	11	1,038	55.0
	12	1,083	55.6
	13	1,120	56.1
	14	1,148	56.5
	15	1,174	56.9
	16	1,194	57.3
1 August	1	49.8	18.1
	2	239	30.3
	3	449	37.4
	4	618	42.5
	5	757	46.1
	6	872	48.5
	7	971	50.2
	8	1,064	51.7
	9	1,152	53.0
	10	1,232	54.1
	11	1,296	55.0
	12	1,346	55.6
	13	1,385	56.1
	14	1,417	56.5
	15	1,445	56.9
	16	1,468	57.3

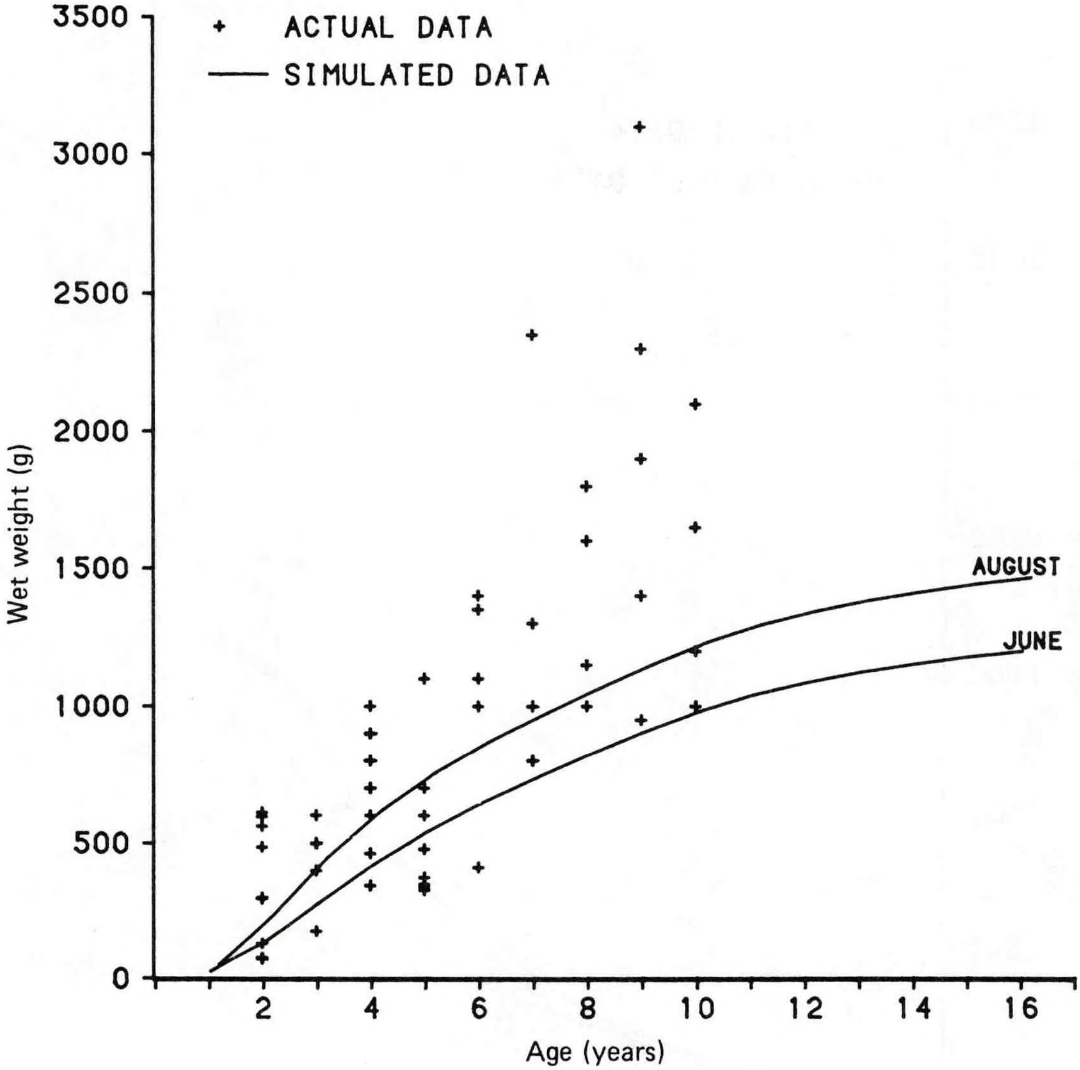

Figure 13.--Comparison of actual and simulated age-weight data for adult walleye pollock. Actual data were measured in 1979; simulated data were for 1 June and 1 August 1979. (These dates were closer to actual dates of measurement than 1 July, which was not graphed to simplify the figure.)

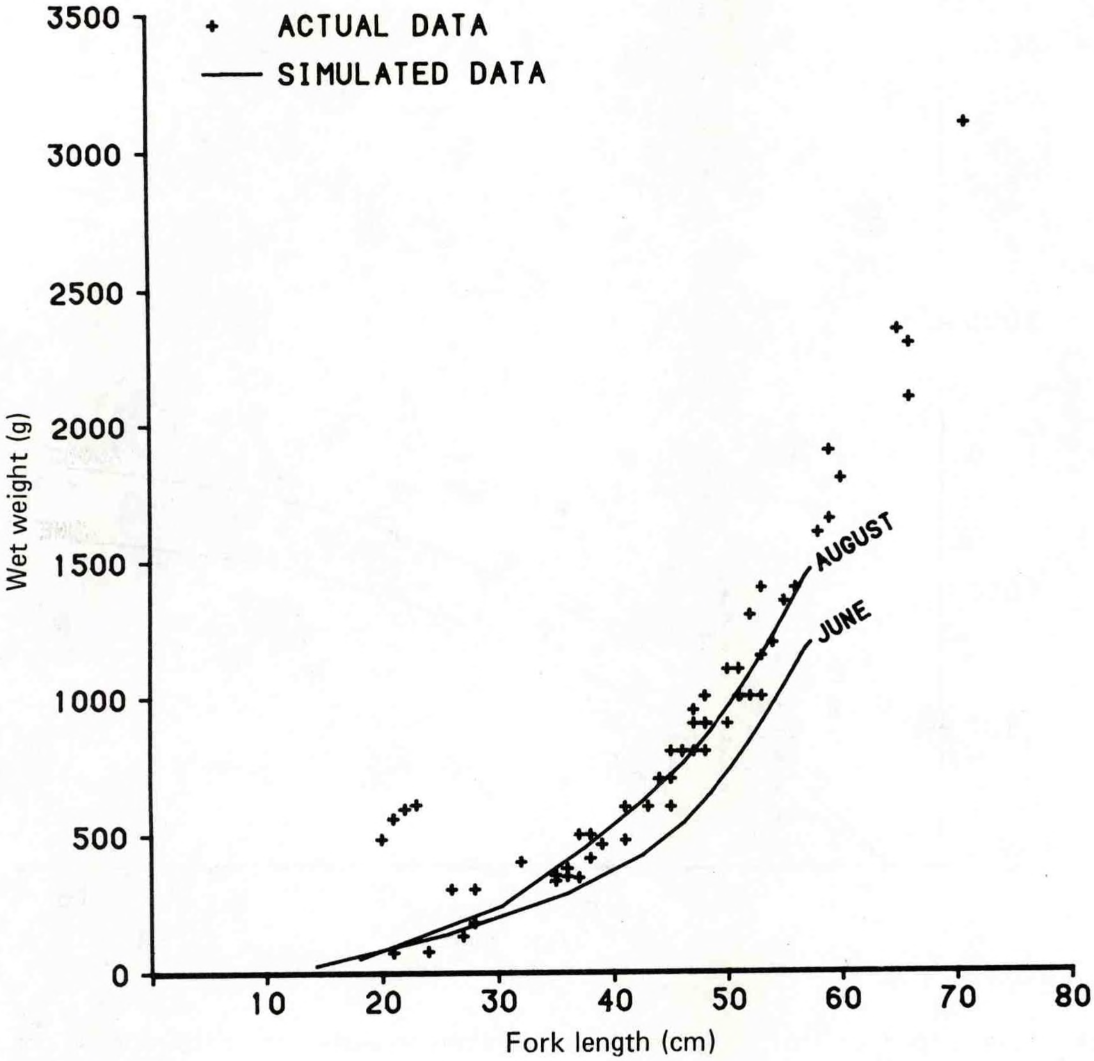

Figure 14.--Comparison of actual and simulated length-weight data for adult walleye pollock. Actual data were measured in 1979; simulated data were for 1 June and 1 August 1979. (These dates were closer to actual dates of measurement than 1 July, which was not graphed to simplify the figure.)

Table 25.--Analysis of variance of adult walleye pollock weights by age and month (1979 data).

Source of variation	Sum of squares	df	Mean square	F ratio
Main effects	1.335×10^7	9	1.48×10^6	9.80[a]
Age	1.235×10^7	8	1.54×10^6	10.19[a]
Month	136	1	136	0.001
Two-way interactions				
Age by month	1.302×10^6	6	2.17×10^5	1.43
Explained	1.466×10^7	15	9.77×10^5	6.45[a]
Residual	6.513×10^6	43	1.51×10^5	
Total	2.117×10^7	58	3.65×10^5	

a/ Significant at the 95% level.

empirical relationships based on length and sex from Smith and Bakkala (1982:49). The sex ratios used (parameters P_{20} and P_{120}) were empirically reasonable from Pereyra et al. (1976:table IX-19).

Since pollock lengths in the simulations were reasonably realistic, as discussed in the earlier section on the validity of pollock lengths, the population size of the mature portion in each pollock cohort must therefore also be considered realistic.

3.6. Validity of the Total Number of Pollock Ova Spawned or Surviving

The total number of pollock ova spawned in a given breeding season (variable ETT) is simulated in POL as an empirical function of pollock population numbers, sex ratios, lengths (maturities), and weights (Knechtel and Bledsoe 1981). The realism of the total number of pollock ova spawned, therefore, is an indicator both of the realism of the simulation of these quantities and the realism of the empirical functions used to calculate ETT. Table 26 shows the simulated total numbers of pollock eggs spawned and surviving to hatch in spring, 1964-80. The values for simulated year 1977 (5.22×10^{10} ova/100 km^2 spawned, 6.53×10^9 eggs/100 km^2 surviving to hatch) seem close to the range of pollock egg and larval densities (equivalent to 1.224×10^9 to 8.181×10^9 eggs/100 km^2 and 1.843×10^9 to 7.835×10^9 larvae/100 km^2) found by Waldron and Vinter (1978:table 8) from 16 April to 15 May 1977. This comparison is only approximate--one would expect the model values to be higher than the measured values, because the model values represent all pollock eggs spawned during an entire breeding season. In contrast, the values measured by Waldron and Vinter were average values over time spans of 4-13 days (not the

Table 26.--Simulated production and survival of walleye pollock eggs, 1964-80.

Year	Total ova spawned		Total eggs surviving to hatch	
	10^9 ova/100 km^2	ova/m^2	10^9 eggs/100 km^2	eggs/m^2
1964	62	620	7.8	78
1965	61	610	7.6	76
1966	60	600	7.5	75
1967	60	600	7.5	75
1968	58	580	7.3	73
1969	58	580	7.2	72
1970	56	560	7.0	70
1971	51	510	6.4	64
1972	46	460	5.7	57
1973	41	410	5.2	52
1974	39	390	4.9	49
1975	42	420	5.3	53
1976	47	470	5.9	59
1977	52	520	6.5	65
1978	54	540	6.7	67
1979	52	520	6.5	65
1980	49	490	6.1	61

entire breeding season), measured after the occurrence of unknown losses to predators and other sources.

3.7. Validity of Plankton Biomasses

The simulated phytoplankton, copepod, and euphausiid biomasses should not be expected to be extremely similar to the actual populations. This is because of the simplifications made in the model. For example, the simulated biomasses were each considered to consist of only one species, with every individual of the species being exactly the same, having the same body weight and length throughout the year. A goal was that the range of food concentrations encountered by the simulated pollock be qualitatively similar to food concentrations actually available. Graphical comparison of simulated values with reasonable values (determined from data in Meshcheryakova 1970a, b) in Figures 15 and 16 indicates that this goal of qualitative similarity was achieved, although more detailed data might show that there were statistically significant differences. The samples described by Meshcheryakova had been collected using a Juday net made of No. 38 silk gauze with a 37-cm mouth diameter.

Figure 17 shows the percentages of the simulated zooplankton biomass which consisted of copepods or euphausiids at different times of the year. An interesting feature is that the simulated euphausiid biomass becomes larger than the simulated copepod biomass for a short time period (around August) while the total simulated zooplankton biomass is approaching its minimum for the summer.

Figure 18 compares simulated total zooplankton biomass concentrations, assuming a 50 m effective depth, with mean values sampled at different seasons

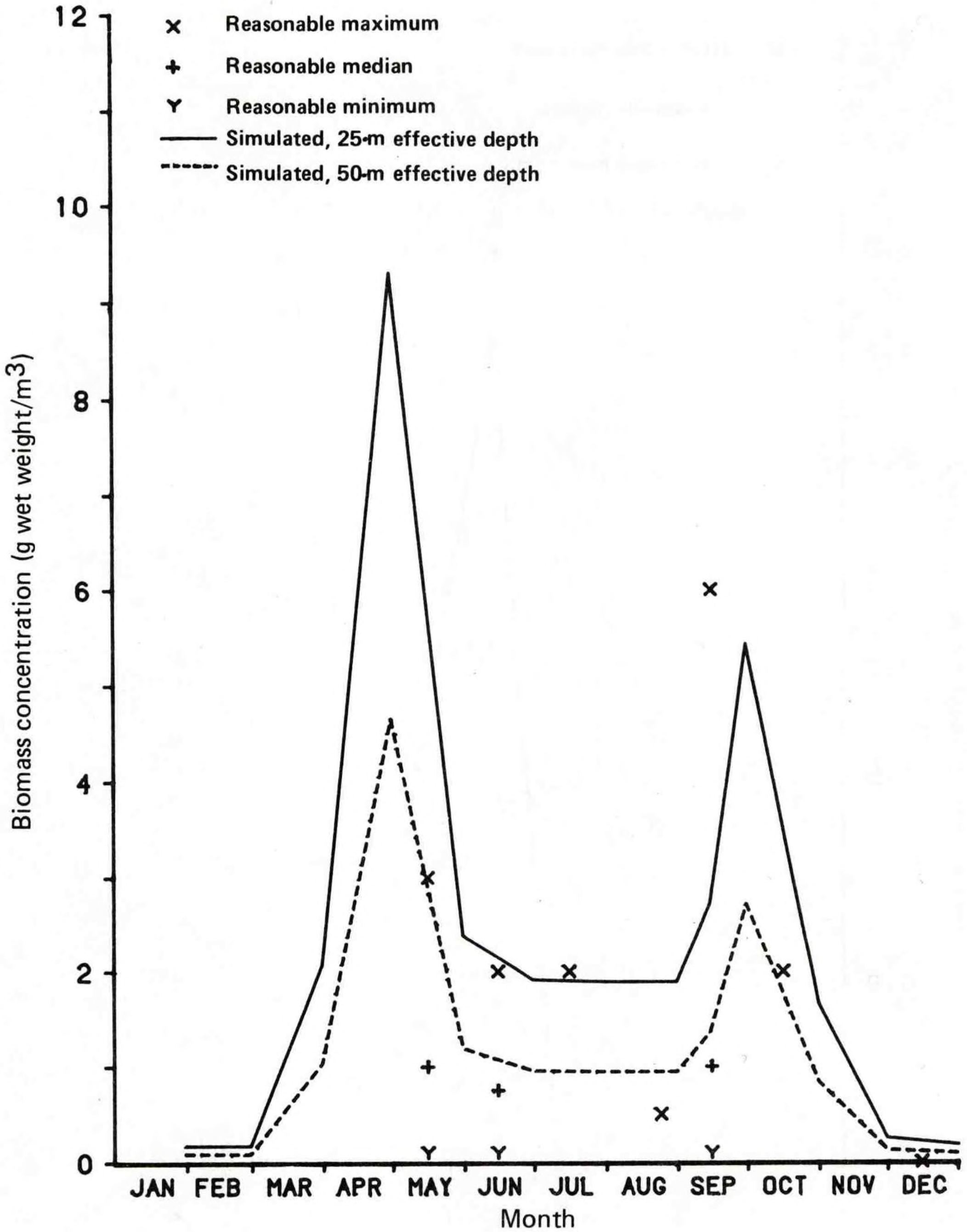

Figure 15.--Comparison of actual and simulated phytoplankton biomass concentrations in 1964. Actual concentrations were reasonable from Meshcheryakova (1970a,b). Simulated concentrations were calculated assuming 1 g C = 20 g wet weight.

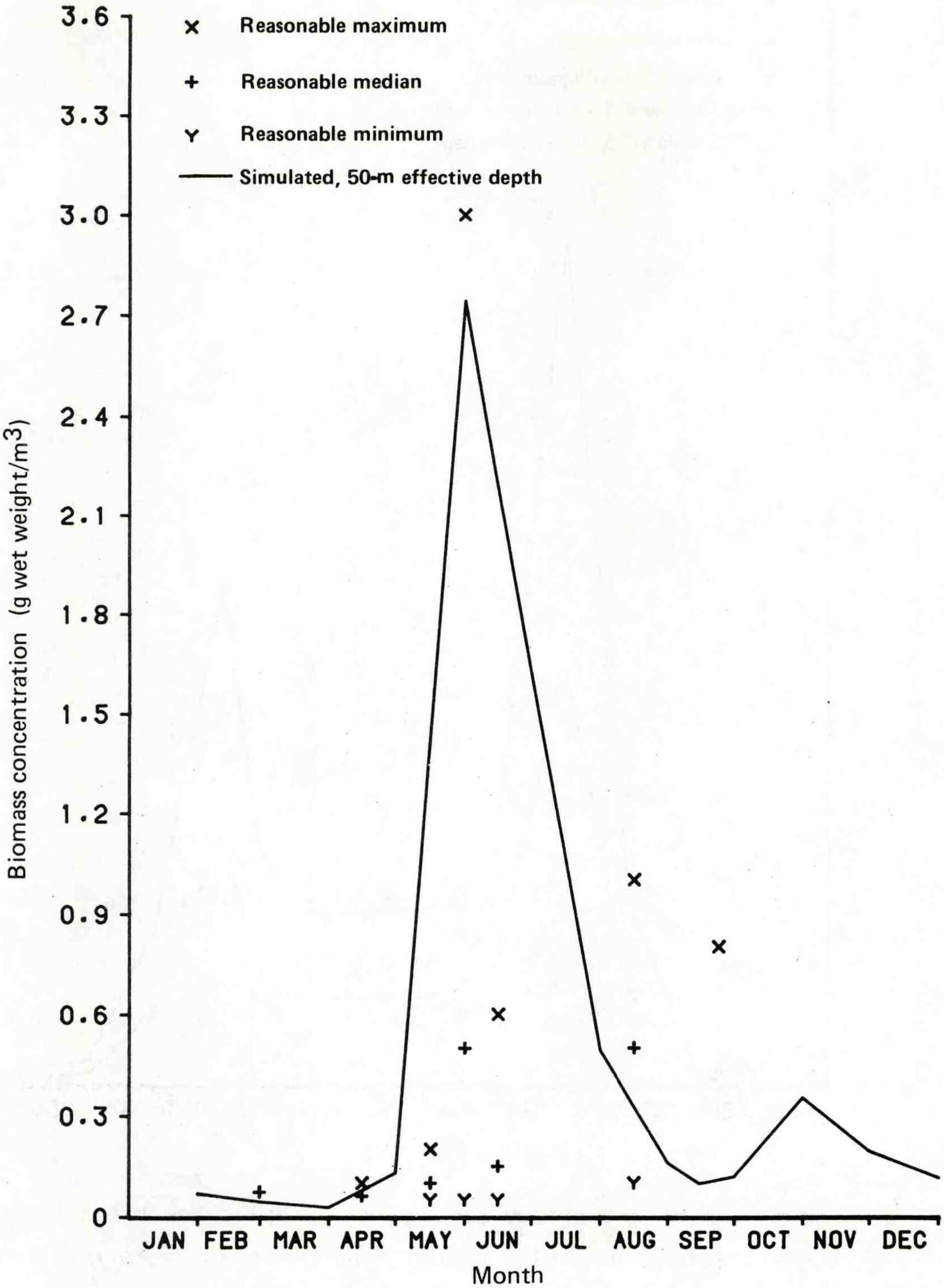

Figure 16.--Comparison of actual and simulated zooplankton biomass concentrations. Actual concentrations were reasonable from Meshcheryakova (1970a,b) using data from 1960, 1962, or 1964. Simulated concentrations were for 1964.

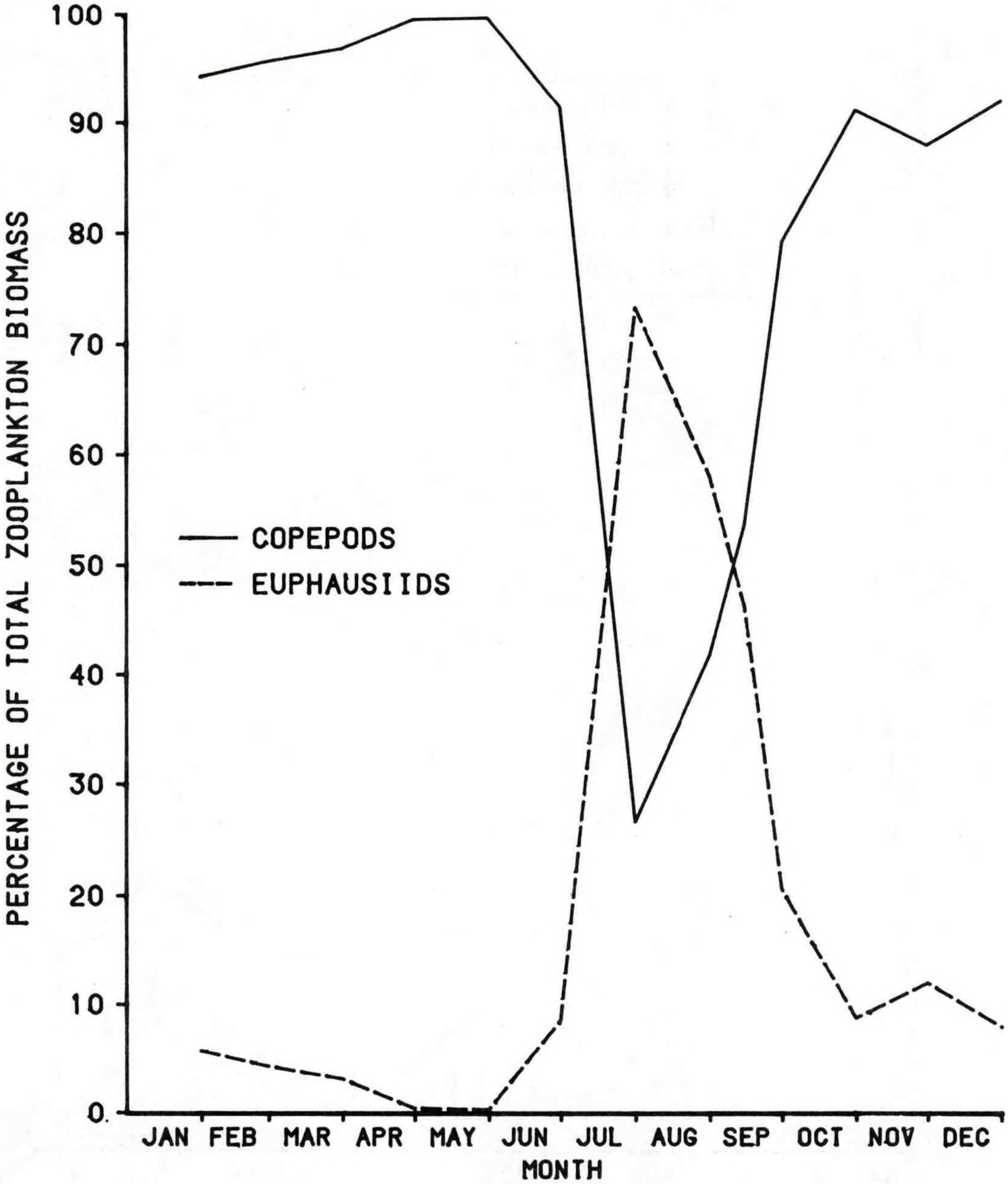

Figure 17.--Comparison of the relative percentages of simulated copepods and euphausiids during 1964.

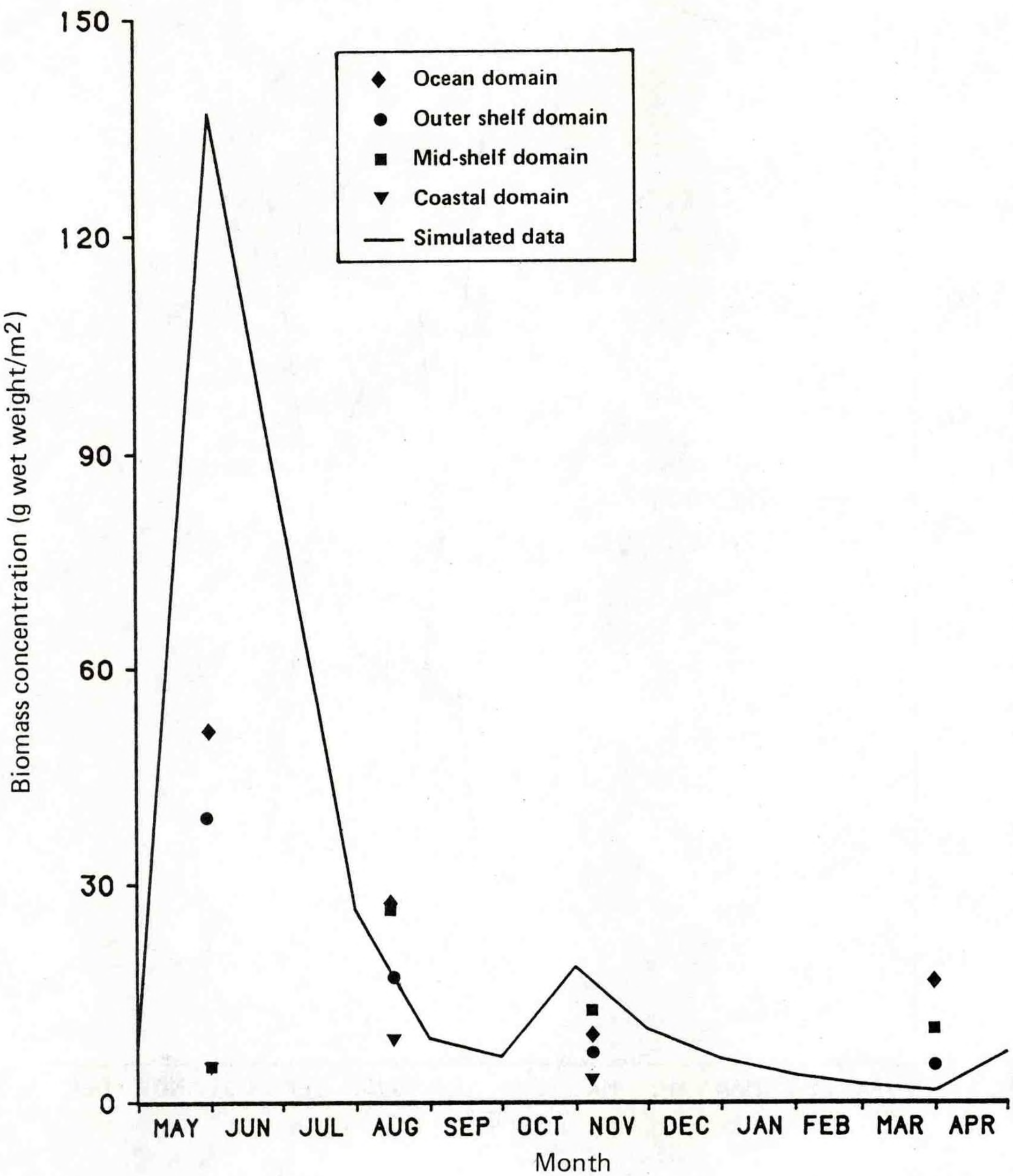

Figure 18.--Comparison of simulated zooplankton biomass concentrations with actual mean biomass concentrations measured in four hydrographic domains of the eastern Bering Sea in 1975-76 (Cooney 1981:fig. 57-7); simulated concentrations were also for 1975-76.

in four hydrographic domains of the southeastern Bering Sea (Cooney 1981:fig. 57-7). Zooplankton samples were collected using a 0.333-mm mesh Nitex 1-m net towed vertically at a speed of about 1 m/second; samples were preserved in formalin (Cooney 1978:253-254). The dry weights given by Cooney were converted to wet weights assuming that 0.15 g dry weight = 1.0 g wet weight (Ikeda and Motoda 1978:335).

Cooney (1981:fig. 57-10) also found that the minimum seasonal values for the oceanic, shelf-break, mixed, and combined middle-shelf and coastal communities were respectively 13, 7, 7, and 7 g wet weight/m^2, and that the maximum values were respectively 37, 180, 60, and 12 g wet weight/m^2. The minimum simulated value (1.3 g wet weight/m^2) might be significantly lower than the minimum values, but the maximum simulated value (about 140 g wet weight/m^2) seems comparable to the maximum values.

4. SIMULATION EXPERIMENTS

Sets of simulations using different combinations of parameters and initial conditions were performed in order to partially explore the behavior of POL. In some cases, though not always explicitly mentioned, parameters were also varied which governed the maximum number of years to be simulated (parameter TL) and the elapsed time between printouts of data. The results of these simulation experiments are described in the following sections.

4.1. Recovery from Overfishing

The simulations in this section were designed to explore whether the model pollock population would recover from overfishing. An additional goal was to explore whether multiple stationary distributions existed for the model, with the model pollock populations recovering to different stationary distributions if fishing was stopped at different times.

As an indication of the size of the spawning pollock biomass in the simulations, the total number of ova laid in spring both before and after the cessation of fishing was graphed in Figure 19 and listed for typical examples in Table 27 (the simulation values listed which used initial conditions from year 20 also used the initial condition $N_1 = 1.33$). In all cases, the spawning biomass recovered from overfishing in 9-16 yr after fishing was stopped, in the sense that the total number of ova produced had stabilized to within ±20% of the final stationary value of about 6.31×10^{10} ova/100 km^2.

To produce these results, the simulated pollock population was first fished to extinction by using the reference set of parameters and initial conditions (Knechtel and Bledsoe 1981:section IV), except that maximum fishing

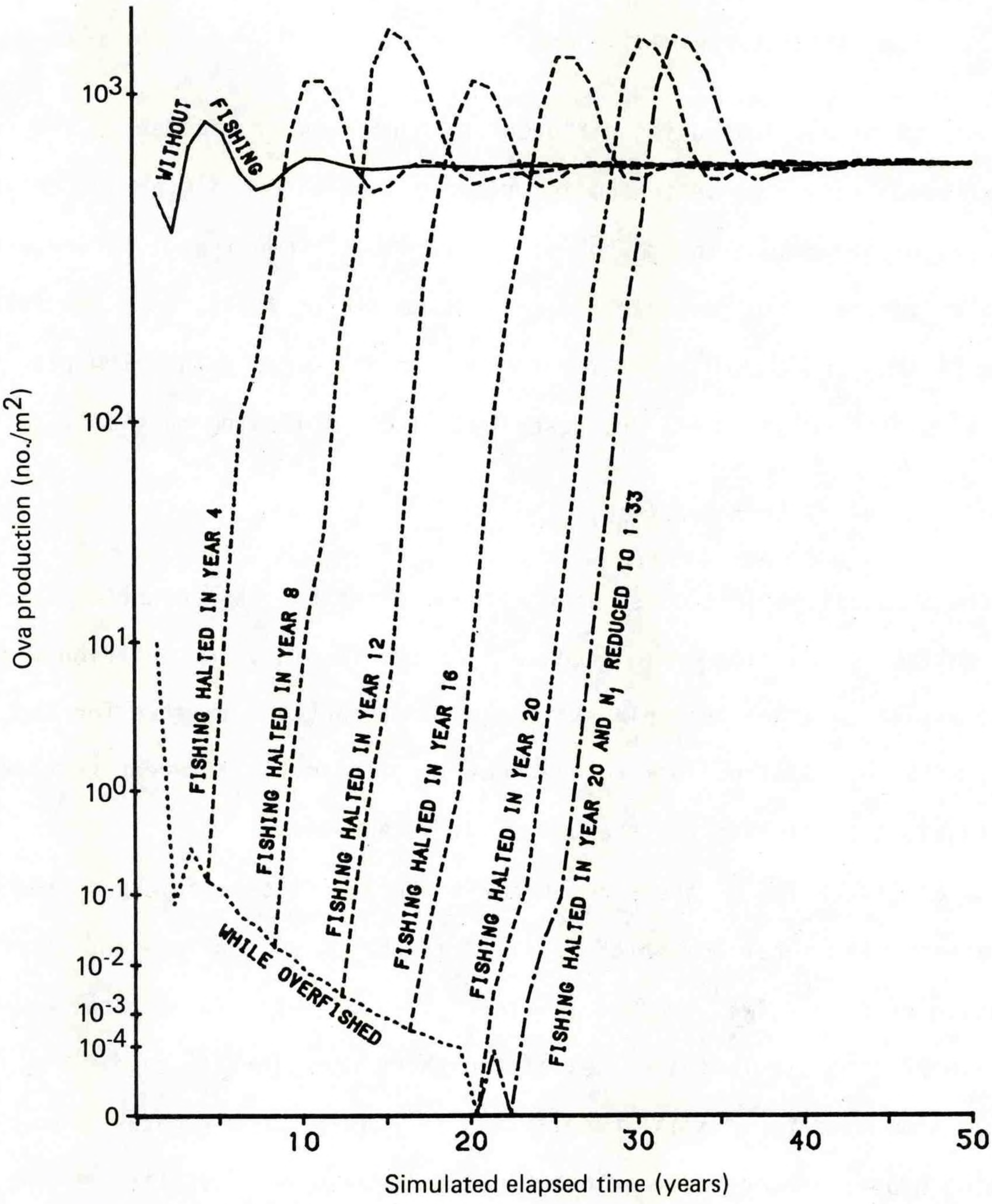

Figure 19.--Simulated total ova production of walleye pollock, showing population recoveries from different stages of overfishing. The transformation $Y^{1/6}$ was used to scale the Y-axis, because details were obscured using linear or logarithmic scales.

Table 27.--Simulated total walleye pollock ova production under conditions without fishing (F = 0), while overfished (F = 6.4 $year^{-1}$), and while recovering from overfishing (F = 0).

Simulated year	Without fishing (ova/m^2)	While overfished (ova/m^2)	After overfishing was stopped[a/] Case 1 (ova/m^2)	Case 2 (ova/m^2)	Case 3 (ova/m^2)
1	5.4×10^{2}	9.8			
2	4.2×10^{2}	7.5×10^{-2}			
3	7.3×10^{2}	3.0×10^{-1}			
4	8.5×10^{2}	1.4×10^{-1}			
5	7.8×10^{2}	1.0×10^{-1}	9.4		
6	6.2×10^{2}	5.2×10^{-2}	9.9×10^{1}		
7	5.5×10^{2}	3.8×10^{-2}	1.6×10^{2}		
8	5.7×10^{2}	1.9×10^{-2}	3.5×10^{2}		
9	6.3×10^{2}	1.4×10^{-2}	7.5×10^{2}		
10	6.7×10^{2}	7.0×10^{-3}	1.1×10^{3}		
11	6.6×10^{2}	5.0×10^{-3}	1.1×10^{3}		
12	6.4×10^{2}	2.5×10^{-3}	9.1×10^{2}		
13	6.3×10^{2}	1.8×10^{-3}	6.2×10^{2}	1.9×10^{-1}	
14	6.2×10^{2}	9.1×10^{-4}	5.4×10^{2}	1.7	
15	6.3×10^{2}	6.5×10^{-4}	5.6×10^{2}	6.9	
16	6.3×10^{2}	3.3×10^{-4}	6.2×10^{2}	6.9×10^{1}	
17	6.3×10^{2}	2.3×10^{-4}	6.6×10^{2}	2.9×10^{2}	
18	.	1.2×10^{-4}	6.4×10^{2}	5.6×10^{2}	
19	.	8.5×10^{-5}	6.3×10^{2}	8.5×10^{2}	
20	.	0	6.2×10^{2}	1.1×10^{3}	
21	.	0	6.2×10^{2}	1.0×10^{3}	6.6×10^{-5}
22	.	0	6.3×10^{2}	8.0×10^{2}	0
23	.	.	6.4×10^{2}	6.0×10^{2}	1.9×10^{-3}
24	.	.	6.4×10^{2}	5.5×10^{2}	2.4×10^{-2}
25	.	.	6.4×10^{2}	5.8×10^{2}	8.8×10^{-2}
26	.	.	6.3×10^{2}	6.2×10^{2}	1.4
27	.	.	6.3×10^{2}	6.4×10^{2}	1.2×10^{1}
28	.	.	6.3×10^{2}	6.3×10^{2}	5.5×10^{1}
29	.	.	.	6.2×10^{2}	2.3×10^{2}
30	.	.	.	6.2×10^{2}	4.4×10^{2}
31	.	.	.	6.3×10^{2}	1.0×10^{3}
32	.	.	.	6.3×10^{2}	1.4×10^{3}
33	.	.	.	6.4×10^{2}	1.3×10^{3}
34	.	.	.	6.4×10^{2}	1.1×10^{3}
35	.	.	.	6.3×10^{2}	7.9×10^{2}
36	.	.	.	6.3×10^{2}	6.0×10^{2}
37	.	.	.	6.3×10^{2}	5.7×10^{2}
38	.	.	.	.	5.9×10^{2}
39	.	.	.	.	6.1×10^{2}
40	.	.	.	.	6.1×10^{2}
41	.	.	.	.	6.1×10^{2}
42	.	.	.	.	6.2×10^{2}
43	.	.	.	.	6.3×10^{2}
44	.	.	.	.	6.4×10^{2}
45	.	.	.	.	6.4×10^{2}
46	.	.	.	.	6.4×10^{2}
47	.	.	.	.	6.4×10^{2}
48	.	.	.	.	6.3×10^{2}

a/ Time when overfishing was halted: Case 1, year 4; case 2, year 12; case 3, year 20. In case 3, the total remaining population of pollock, variable N_1, also was reduced to 1.33 fish/100 km^2.

mortality rates, F_1 to F_{20}, were set equal to 6.4 year^{-1}, and the length at 50% maximum vulnerability to the fishery, P_{84}, was set equal to 20 cm. A graph of resulting fishing mortality rates as a function of length is shown in Figure 20. The simulation was started on 1 September of year 0; all pollock became extinct before 23 April of year 21. The PSVs from this simulation on 13 May of simulated years 4, 8, 12, 16, and 20 were used as initial starting conditions for the differential equations of the model for simulations with no fishing (F_1 through F_{20} were set to 0).

Another simulation with no fishing was made using the initial conditions from year 20, but the initial number of pollock in cohort 1 (the only surviving pollock cohort) was set to 1.33 per 100 km^2 (instead of the original 59.083 per 100 km^2) so that only 1.1 pollock per 100 km^2 would survive to spawn the next year. As a comparison, a simulation was also made using the reference set of parameters and initial conditions without fishing (i.e., F_1 to F_{20} were set to 0).

In every case, making allowance for the approximately 2 significant digit numerical integration accuracy used, the same stationary distribution of PSVs occurred after the cessation of fishing, although varying amounts of simulated time were needed to arrive at the distribution. This indicates that the simulated pollock population is able to recover from severe overfishing, and that simulated extinction is inevitable (i.e., is an "attractor") only at very low population levels after fishing is stopped. For example, extinction would have been an attractor if the initial conditions from year 20 had been used, but with the initial number of pollock in cohort 1 set to some number only slightly greater than 1 (e.g., 1.01 pollock/100 km^2). In this case, less than 1 pollock/100 km^2 would have survived to spawn, which was regarded as

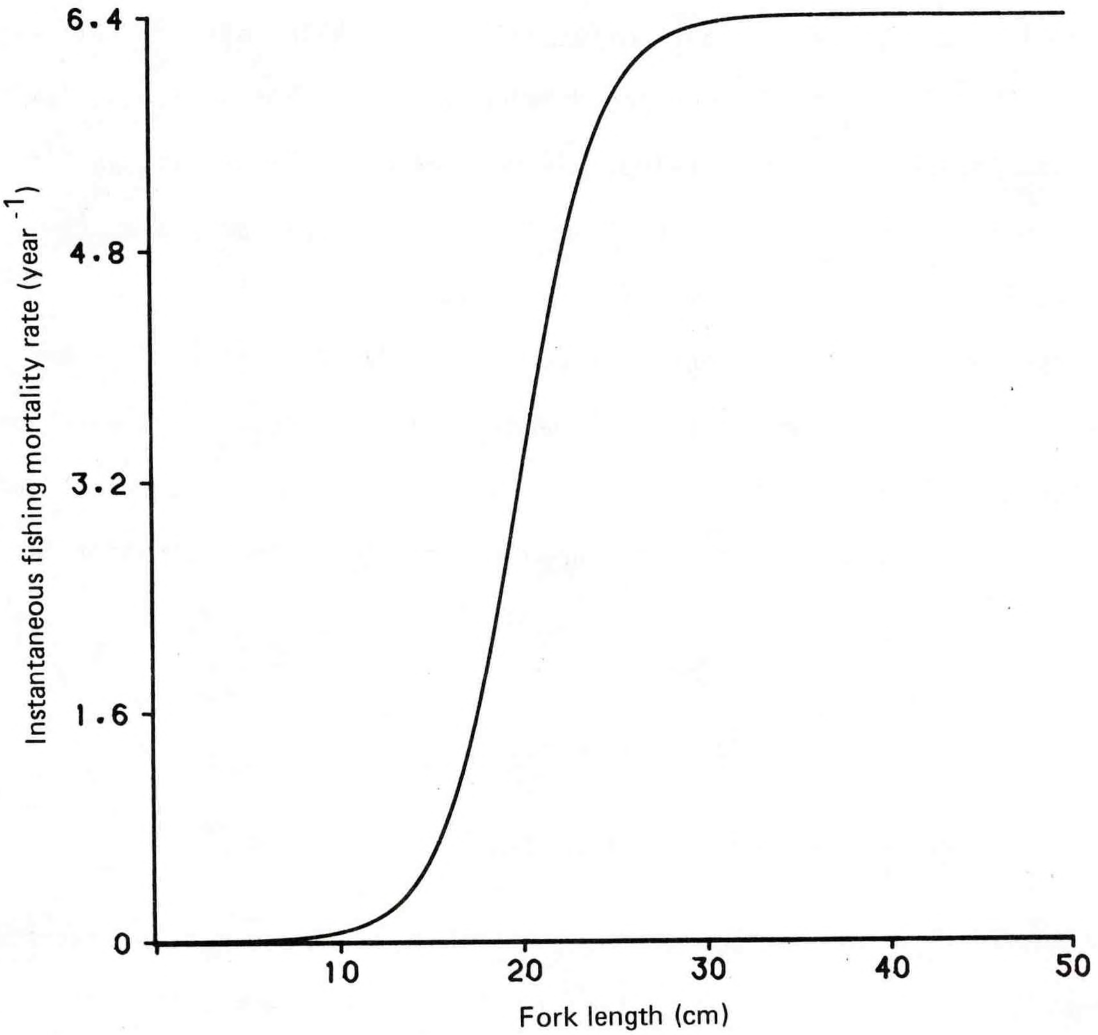

Figure 20.--Simulated fishing mortality rates of walleye pollock, as a function of fork length, which were used to model overfishing. Parameter values used were F = 6.4 $year^{-1}$ (=asymptotic maximum fishing mortality rate), and P_{84} = 20 cm (=length at 50% maximum vulnerability to fishery).

extinction (parameter NMIN, the population level at which extinction was assumed to occur, was equal to 1 pollock/100 km^2). Allee effects (Allee et al. 1949:395-396), such as increased difficulty in finding a mate at low population levels, were not modeled. If such effects are significant in pollock populations, then recovery from population levels as low as the simulated levels might not actually be possible.

These results provide initial evidence that for the present parameter set different nontransient modes of model behavior do not occur for a wide variety of different initial conditions for the PSVs. Consequently, "correct" initial conditions are probably not critical when nontransient model behavior is studied.

4.2. Qualitative Changes in Model Behavior Due to Different Values for Feeding Parameters

4.2.1. Changes Due to Amount of Prey Switching

Actual parameters for pollock prey switching have apparently never been measured. The goal of the simulations in this section is to point out the difference in the response of the simulated euphausiid population to increases in the pollock fishing mortality rate, depending on whether pollock prey switching was allowed or not.

For simulations discussed in this section, the reference set of parameters and initial conditions was used (Knechtel and Bledsoe 1981:section IV), except immigration of juvenile pollock was allowed (P_{74}=10). When there was no fishing (F_1 to F_{20}=0) and after initial transient variations in population levels had faded out, the euphausiid population levels were virtually the same either with (P_{76}=0.06) or without (P_{76}=0) pollock prey switching. The final average yearly simulated standing stock of euphausiids was 3.3 g wet weight/m^2 with P_{76}=0.06, and about 3.6 g wet weight m^2 with P_{76}=0.

Using the same set of parameters and initial conditions, but with heavy fishing (F=2.4 or 3.0 $year^{-1}$) and without pollock prey switching (P_{76}=0), the model euphausiids were completely extinct within 14 simulated years. In contrast, the euphausiids did not become extinct using these parameters and initial conditions with prey switching (P_{76}=0.06). The euphausiids also did not become extinct with no prey switching if there was less fishing pressure; no euphausiid extinction occurred for conditions with P_{76}=0 and F=0.6-1.8 $year^{-1}$.

Due to the shape of the simulated fishery vulnerability curve (e.g., Figure 20), there was higher fishing pressure on the longer, more cannibalistic pollock than on the smaller pollock. An explanation for the euphausiid extinctions is that the higher fishing mortality rates on the longer, more cannibalistic pollock reduced the population numbers of cannibalistic cohorts, resulting in less cannibalism and large (though fluctuating) biomasses of smaller pollock in the model. The smaller pollock consumed relatively large amounts of euphausiids. With prey switching, consumption of euphausiids was reduced to zero if the euphausiid biomass became a small portion of the total available food. However, without prey switching, some consumption of euphausiids continued as long as sufficient levels of other sources of food (e.g., copepods) remained to cause the pollock to continue feeding, which resulted in euphausiid extinction.

Figure 21 shows an example of simulated euphausiid extinction due to lack of prey switching by pollock coupled with heavy fishing mortality (P_{76}=0; F_1 to F_{20} = 2.4 year^{-1}).

4.2.2. Changes Due to Different Parameter Values for Maximum Feeding Rate of Pollock

The purpose of the simulations in this section is to explore some changes in model behavior which occurred as a result of slight changes in parameters determining the maximum feeding rate of simulated pollock. For pollock in the model,

$$\text{maximum feeding rate} = P_7 \times L_i^{P_{119}} \qquad (5)$$

where L_i is fork length, and P_7 and P_{119} are parameters. This equation was modified slightly for newly hatched or potentially spawning pollock. In addition, P_{17} and P_{114} were always set equal to P_7 in simulations discussed in this study.

Values for $\log_{10}P_7$ and P_{119} were calculated as a linear combination of 7 parameters estimated using least squares multiple linear regression on logarithms of 43 data points from Jones (1974:appendix tables VI-VII). It was assumed that these transformed data points had a multivariate normal distribution. Data points used were measured for Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and whiting (*Merlangius merlangus*) weighing 136-1174 g and 23-53 cm in length. It was also assumed that pollock digest food at the same rate that saithe (*Pollachius virens*) was digested in

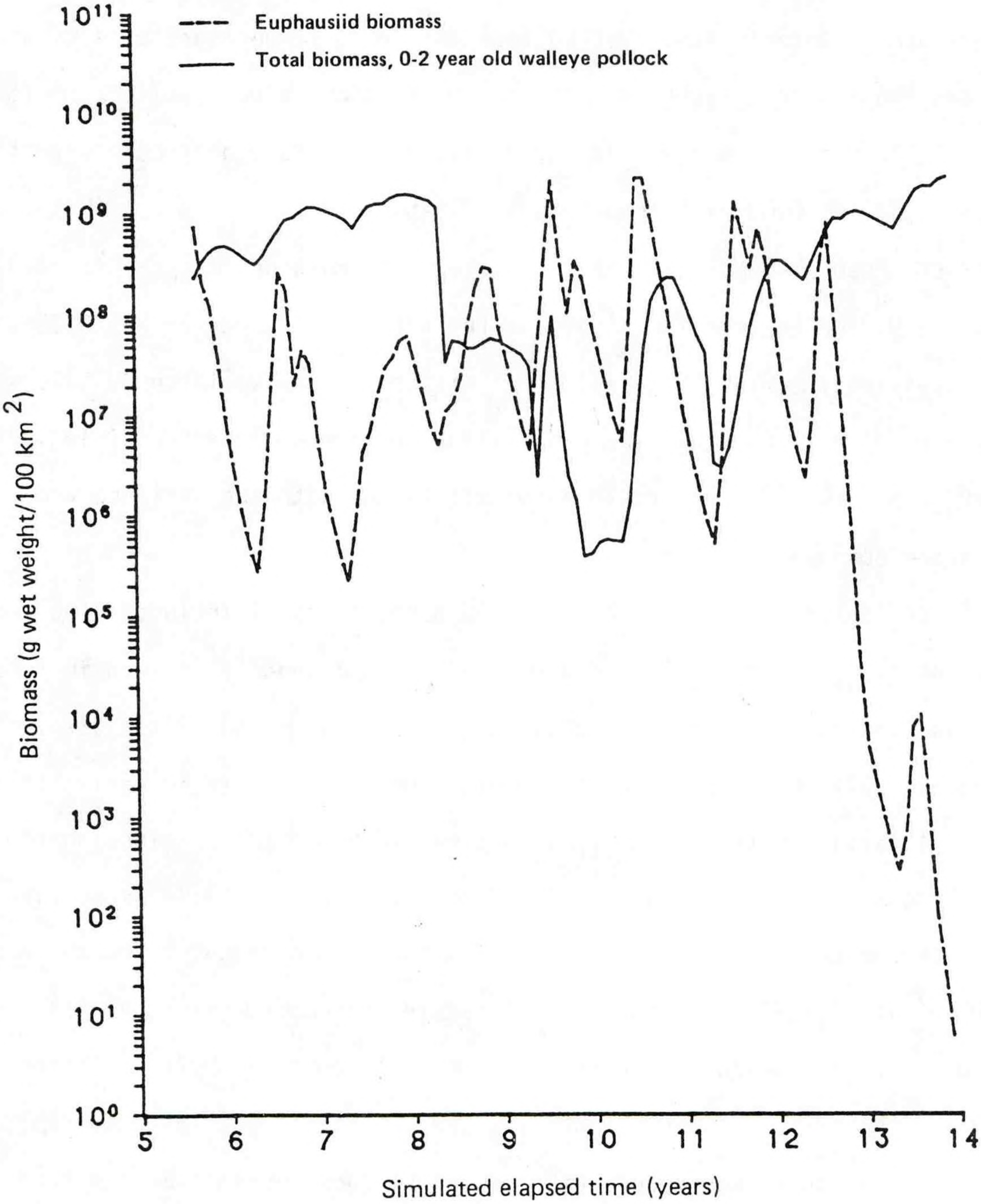

Figure 21.--Simulated euphausiid extinction due to lack of prey switching by walleye pollock (P_{76} = 0) coupled with an intense fishery (F = 2.4 year^{-1}).

some of Jones' experiments, that pollock live at a temperature of 4°C, and that the equilibrium weight (g) of food in the stomach of a pollock of fork length L (cm) which has been feeding at its maximum rate over a long period of time is equal to $0.0004 \times L^3$ (see Daan 1973:table XII).

With these assumptions, the most likely estimate of $\log_{10}P_7$ was -1.39 (i.e., P_7=0.0407 [g/year]/cm$^{P_{119}}$), and the variance of $\log_{10}P_7$ was 0.236. The most likely estimate of P_{119} was 3.09 (unitless), with variance 0.0871. The covariance of $\log_{10}P_7$ with P_{119} was -0.143, and the correlation of $\log_{10}P_7$ with P_{119} was -0.994. The residual df associated with the variance and covariance estimates was 36.

A confidence ellipse which has a 95% probability of including the "true" values of $\log_{10}P_7$ and P_{119} was constructed using methods described in Scheffe (1959:section 2.3) and Draper and Smith (1981:section 2.6). This 95% confidence ellipse is shown in Figure 22. The model POL is sensitive to this amount of variation in P_7 and P_{119}, as shown in Table 28. Extinction of pollock occurred for some values of P_7 and P_{119}, including the "most likely" pair. The values of $\log_{10}P_7$ and P_{119} from the reference set of parameters (P_7=0.107 and P_{119}=2.95) actually fall outside the boundary of the 95% confidence ellipse, although they would be included in a 99.7% confidence ellipse. It is likely that P_7 and P_{119} are correlated with other parameters used in POL, such as parameters determining pollock respiration and food conversion efficiency (P_1, P_2, P_3, P_{117}, P_{118}), but the data needed to estimate joint confidence regions were not available. If improved confidence

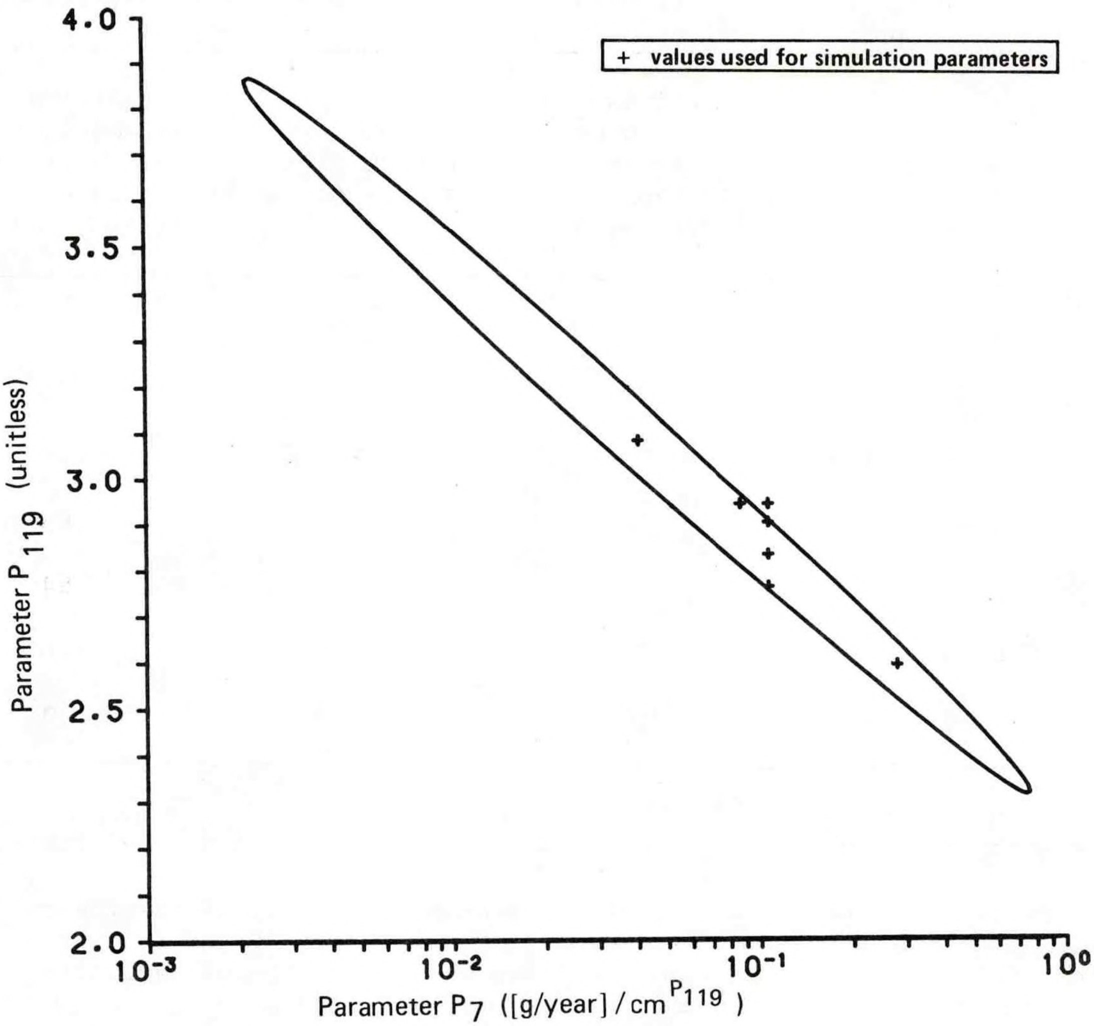

Figure 22.--Graph of a 95% confidence ellipse for the joint distribution of the maximum feeding rate parameters P_7 and P_{119}. Data used to calculate the ellipse was measured for Atlantic gadoids.

Table 28.--Simulated walleye pollock recruitment, maximum length, and annual fishery yield as a function of maximum feeding rate parameters.

P_7 a/	$\log_{10}P_7$	P_{119}	Equilibrium average number of 2-yr-olds on 13 May b/ (10^4/100 km^2)	Maximum fork length on 13 May b/ (cm)	Equilibrium average annual fishery yield for F=0.3 $year^{-1}$ b/ (t/100 km^2)
0.0407	-1.39	3.09	0	0	0
0.087	-1.06	2.95	48	53	88
0.107 c/	-0.97	2.95	53	57	114
0.107 d/	-0.97	2.91	76	57	88
0.107 d/	-0.97	2.84	95	48	54
0.107	-0.97	2.77	120	42	28
0.280	-0.55	2.60	0	0	0

a/ The parameters P_{17} and P_{114} were set equal to P_7 in these simulations.

b/ The final stationary value was usually used. However, if stationary conditions did not occur, an average or maximum calculated from the final 201 yr of a 256-yr simulation was used. A zero (0) indicates that extinction of the entire pollock population occurred.

c/ Values are from the reference set of parameters. All other values for $\log_{10}P_7$ and P_{119} came from within a 95% confidence ellipse shown in Figure 22.

d/ Stationary conditions did not occur during these simulations. The dominant period of fishery yield fluctuations during the final 201 yr of a 256-yr simulation was respectively 6.7 or 8.7 years, for P_{119}=2.91 or 2.84.

regions were constructed taking such correlations into account, and if new data were used which had been measured for pollock, it might be shown that the values which caused pollock extinction in the model actually were unlikely. In addition, the simulation of the smallest sizes of pollock may be more sensitive to the values of P_7 and P_{119} than the larger sizes. For example, with $P_7=0.0407$ and $P_{119}=3.09$, the age-0 (model cohort 1) pollock consistently died of simulated starvation and this caused eventual extinction of the entire pollock population.

4.2.3. Changes Due to Alterations in Relative Vulnerability to Cannibalism

The goal of the simulations performed in this section is to explore how much cannibalism is necessary to control pollock population fluctuations. The simulations demonstrated that cannibalism could both cause and dampen fluctuations in simulated population levels; the simulations also provided examples of different categories of model dynamics. The parameter P_5 determined the relative vulnerability of pollock to cannibalism. The model was originally calibrated with $P_5=1$; if $P_5=0$, no cannibalism could occur in the model. The value $P_5=1$ meant that a copepod (or euphausiid) and a pollock of the same weight were equally preferred as prey by pollock, if otherwise equally available. However, differences in relative biomass of prey categories, or in vulnerability to cannibalism due to changes in preferred depth in the water column, caused differences in availability.

Simulations were performed with the reference set of parameters and initial conditions, except P_5 was in the range 0-1, with $P_{74}=10$. Figure 23 shows some resulting values of logarithms of simulated annual catches of

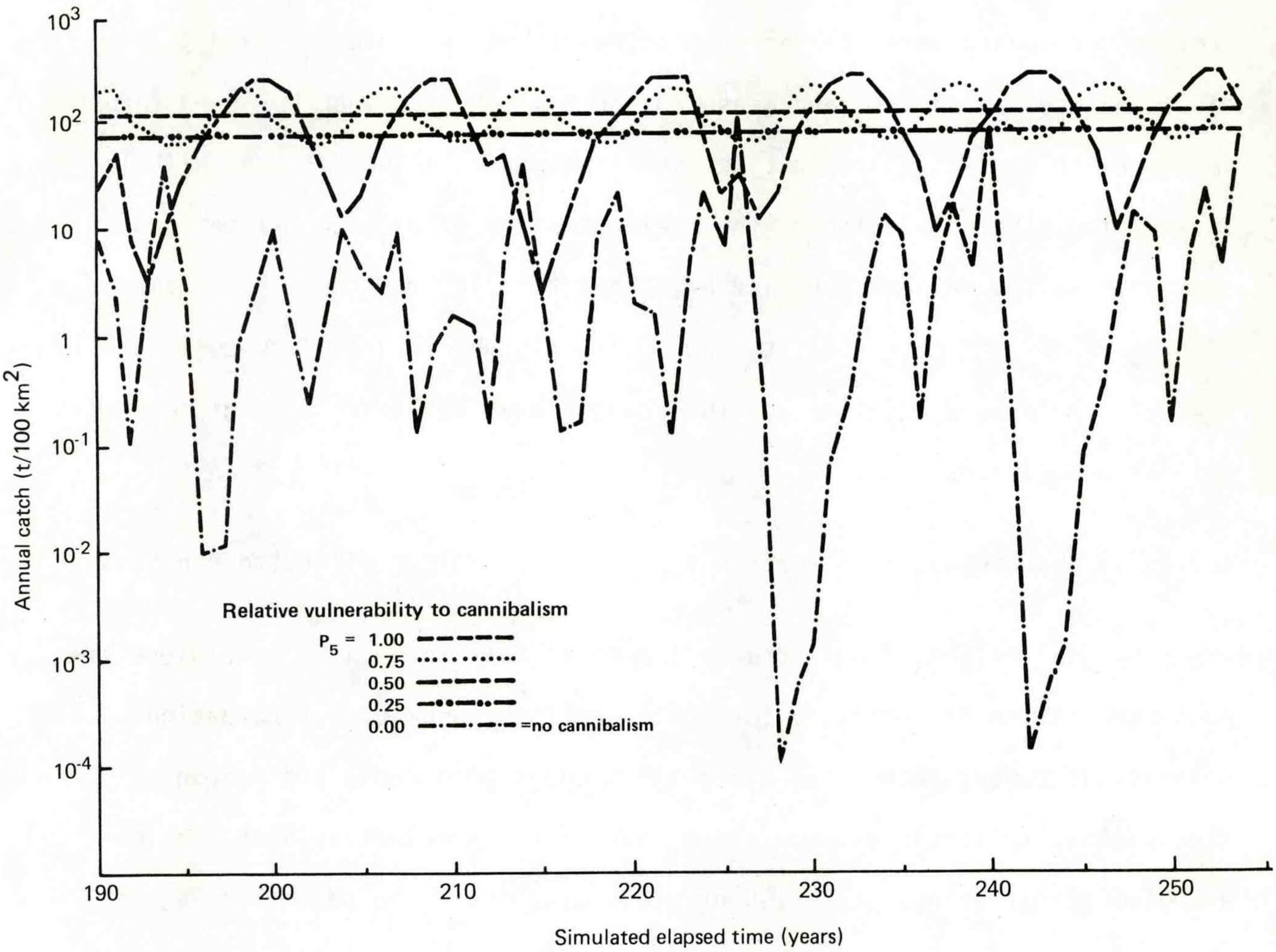

Figure 23.--Graphs of simulated annual walleye pollock catches as a function of relative vulnerability to cannibalism (P_5=0 means no cannibalism). In each case F=0.3 year^{-1}. Simulations with P_5=1.0 or P_5=0.25 were actually stopped in the 48th or 64th simulated year because stationary conditions occurred.

walleye pollock. In order to save computer time, the simulations in which stationary conditions occurred (P_5=0.25, 1.0) were only run for two simulated yr after the detection of stationary conditions. The other simulations (P_5=0, 0.50, 0.75) were run for 256 simulated yr.

The periodogram is a standard tool used in harmonic analysis. The version used in this study was calculated as in Box and Jenkins (1976:section 2.2.1), using a FORTRAN computer program. The periodogram was then normalized so that the sum of the periodogram ordinates at frequencies greater than 0 was equal to 1. Periodograms were calculated using the last 201 data points from each simulation (simulated years 56-256). Unless noted otherwise, the data points were not transformed before the periodograms were calculated. Two statistical tests for periodicity were performed on each periodogram; the results of these tests are summarized in Table 29. The null hypothesis of the statistical tests used is that each observation of the time series being tested is independent of the other values and that all observations have an identical normal (Gaussian) distribution. If this is indeed the case, the time series is known as "white noise." If the null hypothesis is rejected, the time series can be considered "harmonic" or "periodic."

The first test for periodicity used was the cumulative periodogram test described in Hannan (1960:99-101) and Box and Jenkins (1976:section 8.2.4). Suppose the unnormalized periodogram ordinate at frequency 2 x pi x j/n radians is I_j, where n is the number of points in the time series. Then define the cumulative normalized periodogram ordinate at frequency 2 x pi x j/n radians as

$$C_j = \left(\sum_{k=1}^{j} I_k\right)/\left(\sum_{m=1}^{q} I_m\right) \qquad (6)$$

Table 29.--Statistical significance of periodicities in simulated annual catches of walleye pollock, as a function of relative vulnerability to cannibalism (P_5).

P_5	Number of data points in time series	Maximum absolute deviation (DEV)	Siegel's T_{lambda}
0.75	201	0.6123[a]	0.8596[a]
0.50	201	0.6030[a]	0.5969[a]
0.00	201	0.06303	0.03285
0.00[b]	201	0.3394[a]	0.1823[a]

a/ Statistically significant at the 95% level, indicating the presence of periodicity or periodicities. Statistical tests used are described in the accompanying text.

b/ This time series was generated by taking the 5.89463rd root of each original data point, in order to reduce the coefficient of skewness to zero.

where q=(n-1)/2 if n is odd, or q=(n-2)/2 if n is even, and $1 \leq j \leq q$. Then C_j has the expected value j/q, under the null hypothesis of white noise. Let DEV equal the maximum value of $ABS(C_j - j/q)$, where ABS is the absolute value function and $1 \leq j \leq q$. If the time series is white noise, DEV is expected to be close to zero. The approximate significance of any departures of DEV from 0 can be assessed by use of a Kolmogorov-Smirnov test.

The second test for periodicity used was the T_{lambda} test of Siegel (1980). Define the normalized periodogram ordinate Y_j by the equation

$$Y_j = I_j / (\sum_{m=1}^{q} I_m). \tag{7}$$

The expected value of Y_j for $1 \leq j \leq q$ is 1/q under the null hypothesis of white noise. Siegel's T_{lambda} test at the 100 x (1-alpha)% significance level is based on the test statistic

$$T_{lambda} = \sum_{j=1}^{q} MAX (0 , Y_j - lambda \times g_F) \tag{8}$$

where lambda is a parameter in the recommended range 0.4-0.6 (Siegel 1980:347-348), and g_F is the critical value for Fisher's test of periodicity (Fisher 1950:16.59a) at level 100x(1-alpha)%. Since alpha is used to determine g_F, the significance level of Siegel's test must be chosen before T_{lambda} is calculated, so that the resulting T_{lambda} statistic is frequently usable only for a test at that significance level. Only those Y_j greater than lambda x g_F contribute to the size of T_{lambda}.

For the analyses summarized in Table 29, lambda=0.4 and alpha=0.05. The value of g_F was estimated to be 0.07378 for q=100. This was done using a FORTRAN subroutine based on an equation in Fisher (1950:paper 16, eq. 4). The significance of the resulting T_{lambda} statistic was evaluated using a FORTRAN subroutine implementation of an equation in Siegel (1980:eq. 4.1). Using Siegel's test the null hypothesis of white noise was rejected at the 95% level for the time series generated with P_5=0.75 and P_5=0.5. Shimshoni's test (Shimshoni 1971) was performed with an individual significance level of 95% for each $Y_j \geq 1/q$. This was done using a FORTRAN subroutine implementing Shimshoni's (1971) equation 5. These tests showed that the time series generated with P_5=0.75 had a statistically significant cycle with a period of about 8 yr and a statistically significant second harmonic with a period of about 4 yr. Similarly, the time series generated with P_5=0.5 had a statistically significant cycle with a period of about 11 yr.

In contrast, Siegel's test failed to reject the null hypothesis of white noise at the 95% level in the case of the time series generated with P_5=0. Let the observations in this time series be represented by X_i, where i=56,57,58...256. Let the m_x be the mean of the X_i and let s_x^2 be the sample variance of the X_i. Let $Z_i = (X_i - m_x)/(s_x^2 - s_x^2/n)^{0.5}$. If the X_i are indeed a white noise series, they are independent and have an identical normal distribution. Then for large n the Z_i should be approximately independent. Additionally, they should have a Student's t distribution with df=n-1 (Draper and Smith 1981:section 3.1). However, a Kolmogorov-Smirnov goodness-of-fit test showed that the sample cumulative distribution had an approximate probability of <0.001 of occurring under the null hypothesis that the Z_i are independent with a Student's t distribution with df=n-1. Histogram A in Figure 24 shows the original X_i values. Obviously their distribution is skewed. Under the null hypothesis that the X_i are white noise, their coefficient of skewness is expected to equal 0. However, it was 4.95, which

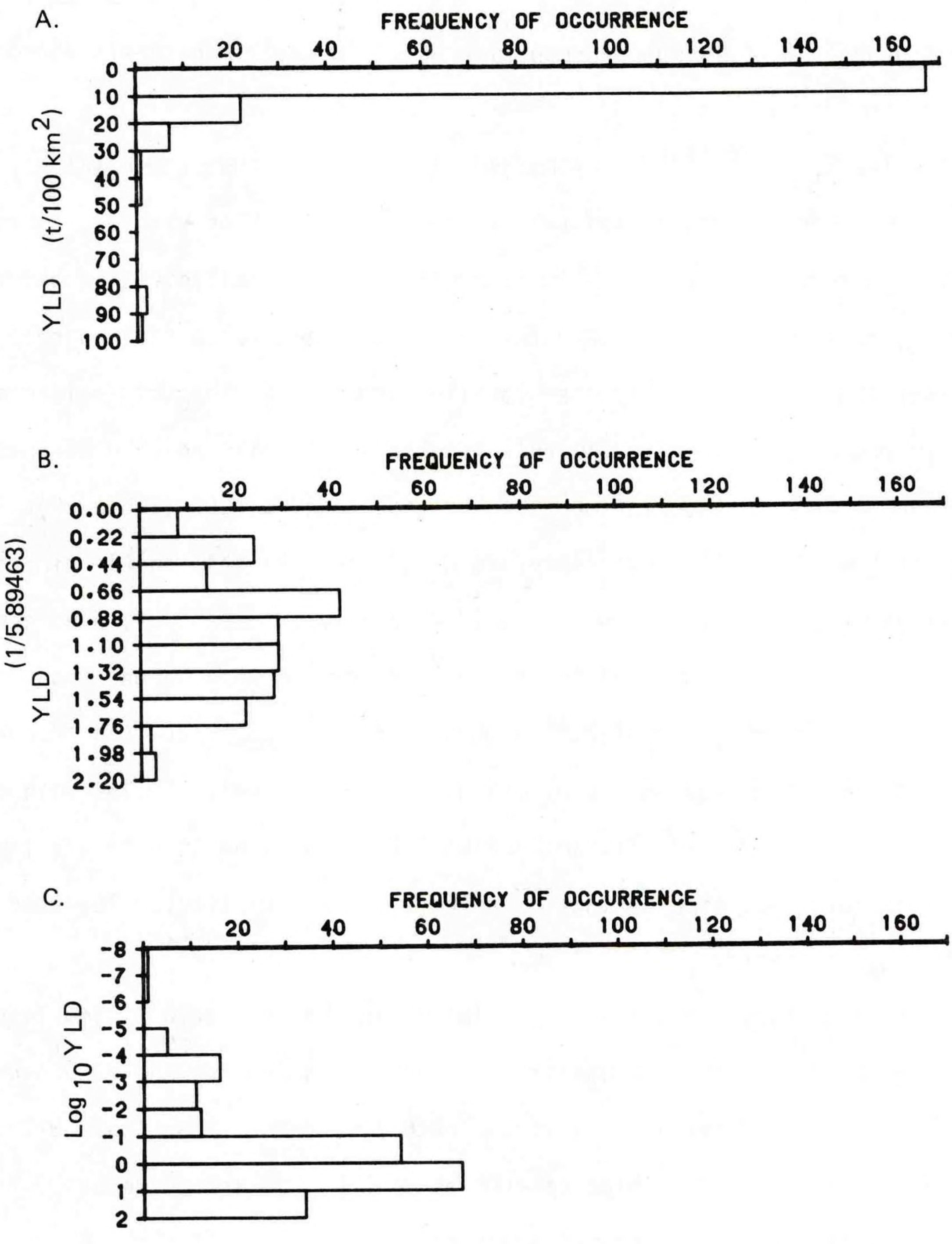

Figure 24.--Histograms of annual walleye pollock fishery yield (YLD), or its transformations, simulated without cannibalism and with F = 0.3 year^{-1}. The last 201 yr of a 256-yr simulation were used for the histograms. (See text for further explanation.)

has a probability of <0.001 of occurring under the null hypothesis (Snedecor and Cochran 1967:section 3.13).

Now let $Z_i = X_i^{1/5.89463}$; Histogram B (Figure 24) shows these values. This particular power transformation reduced the coefficient of skewness to zero and was determined using a FORTRAN subroutine. (The coefficient of skewness of the Z_i was -0.0002.) The transformation $\log_{10}(X_i)$ was also considered, but it skewed the observations in the opposite direction of the original series (Histogram C of Figure 24). The null hypothesis of white noise was rejected at the 95% level for the Z_i time series using Siegel's test (Table 29). Ranked by the size of the corresponding Y_j (largest first), the Z_i time series apparently had periodicities of 15.5, 13.4, 5.2, 9.1, 6.9, 10.0, 4.9, and 100.5 years; the Y_j calculated for these time periods were larger than the critical value (lambda x g_F=0.02951) used in the T_{lambda} statistic and were significant at about the 95% level using Shimshoni's test. Cycles with other time periods were also significant at the 95% level using Shimshoni's test; but the Y_j for these time periods were less than the critical value used in the T_{lambda} statistic.

These results indicated that simulated cannibalism, even at low levels, can minimize population fluctuations. Although cannibalism can also cause fluctuations, these fluctuations appear much less random than those without cannibalism (Figure 23). Three categories of behavior are evident:

1) stationary (equilibrium) behavior;
2) periodic behavior; and
3) behavior with a large pseudorandom (chaotic) component.

Cumulative errors in numerical integration were significant for the time series with $P_5=0$, which displayed a large apparent component of pseudorandom behavior. Figure 25 shows two time series of simulated annual pollock catches. A total of 256 points were contained in each time series. One time series was calculated with ACCRCY=0.005 and TDMIN=2^{-11} (which were the values from the reference set of parameters) so that the numerical integration subroutine attempted to maintain a local accuracy of approximately two significant digits; part of this time series was also shown in Figure 23. The other time series was calculated with ACCRCY=0.0005 and TDMIN=2^{-15}, so that the numerical integration subroutine attempted to maintain a local accuracy of approximately three significant digits. The two series gradually diverge, though they did not differ in the first two significant digits for the first 6 simulated yr. The correlation between the two time series (calculated using the last 201 data points of each series) was only -0.046. Despite this divergence, no difference in the statistical properties of the two time series was detected. A Kolmogorov-Smirnov two-sample test showed no statistically significant differences at the 95% level between the statistical distributions of the last 201 data points (simulated years 56-256) of each time series. The observed significance level was 28%. Similarly, another Kolmogorov-Smirnov two-sample test showed no statistically significant differences at the 95% level in the periodograms calculated from the last 201 data points of each time series. The observed significance level was 35%.

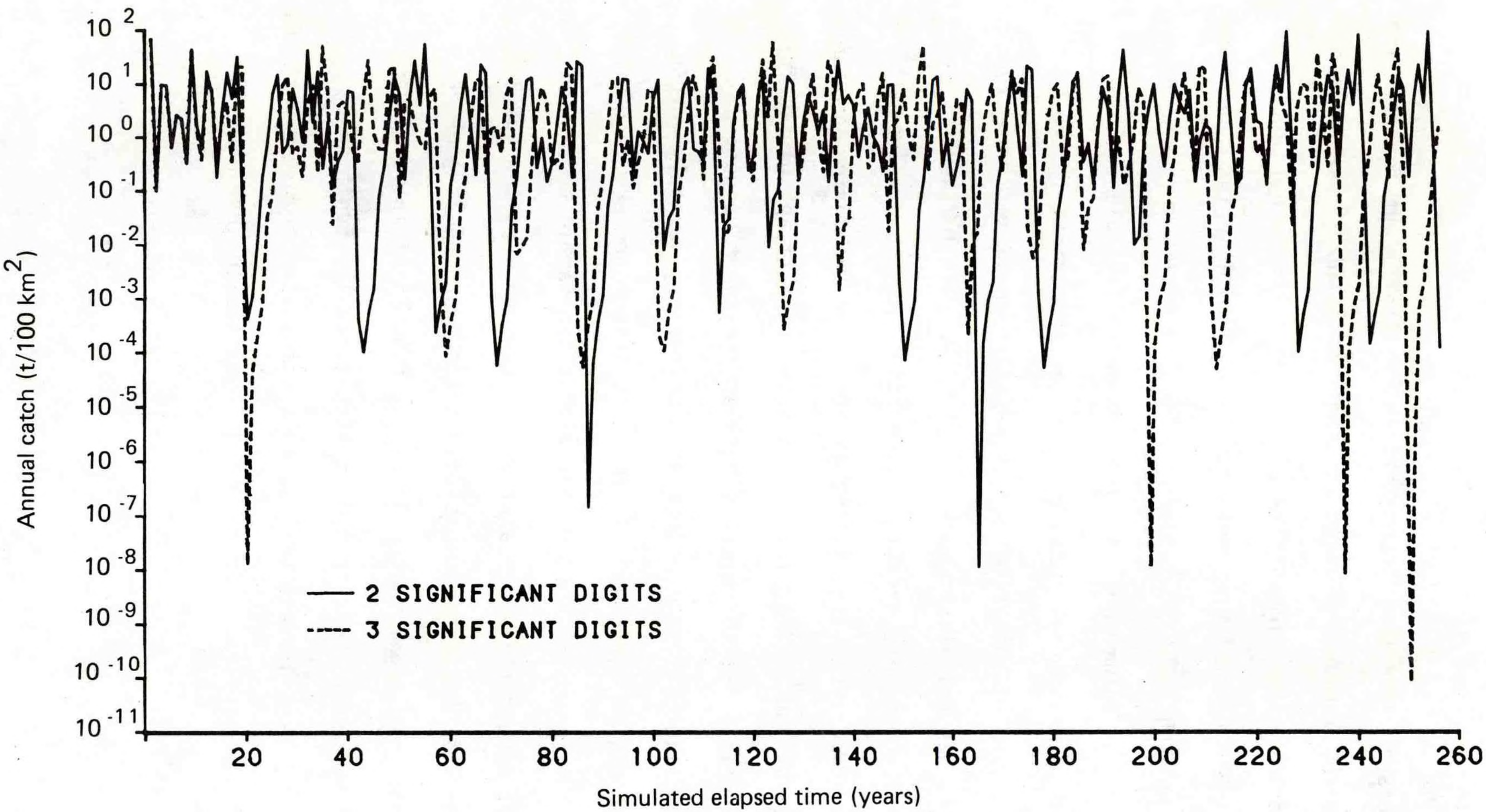

Figure 25.--Simulated annual walleye pollock catches calculated with approximate local numerical accuracy of 2 or 3 significant digits. Cumulative divergence of calculated values is evident. Parameter values used were $P_5=0$ (no cannibalism), $F=0.3$ year^{-1} and $P_{74}=10$ pollock/100 km^2 (possible immigration of cohort-1 pollock allowed).

4.3. Effects of Variation of Length of Recruitment, Maximum Fishing Mortality Rate, and Cannibalism

The primary purpose of the simulation experiments in this section is to explore what combination of length at 50% maximum vulnerability to the fishery (P_{84}) and maximum fishing mortality rate (F) would eventually result in an optimum simulated yield of pollock. The conditions represented by P_{84} and F can be controlled by a fishery management authority; for example, vulnerability to the fishery may depend in part upon net mesh size, and fishing mortality can be an approximate function of nominal fishing effort.

In a search for potential optimums, parameter F was varied from 0 to 3.0 $year^{-1}$, with a step of 0.3 $year^{-1}$. Parameter P_{84} was varied from 10 to 45 cm, with a step of 5 cm. Relative vulnerability to cannibalism (P_5) was allowed to equal 0 (no cannibalism) or 1 in order to give some indication of how results would change under different levels of cannibalism (the model was originally calibrated assuming P_5=1). A total of 162 simulations were run for these combinations of parameters.

Possible immigration of cohort 1 pollock was allowed in these simulations (P_{74}=10). The simulations were allowed to run for 2 simulated yr after the occurrence of stationary conditions (i.e., 1-yr periodicity), but if stationary conditions did not occur the simulations were stopped after 256 yr. The fishing season was assumed to begin on 13 May of each simulated year; so in these simulations, annual fishery catch refers to the total catch of pollock from 13 May of one simulated year until 13 May of the next simulated year.

The results of the 162 simulations are summarized in Figures 26-31 and Tables 30-45. The data points for the isopleths in Figures 26-31 were

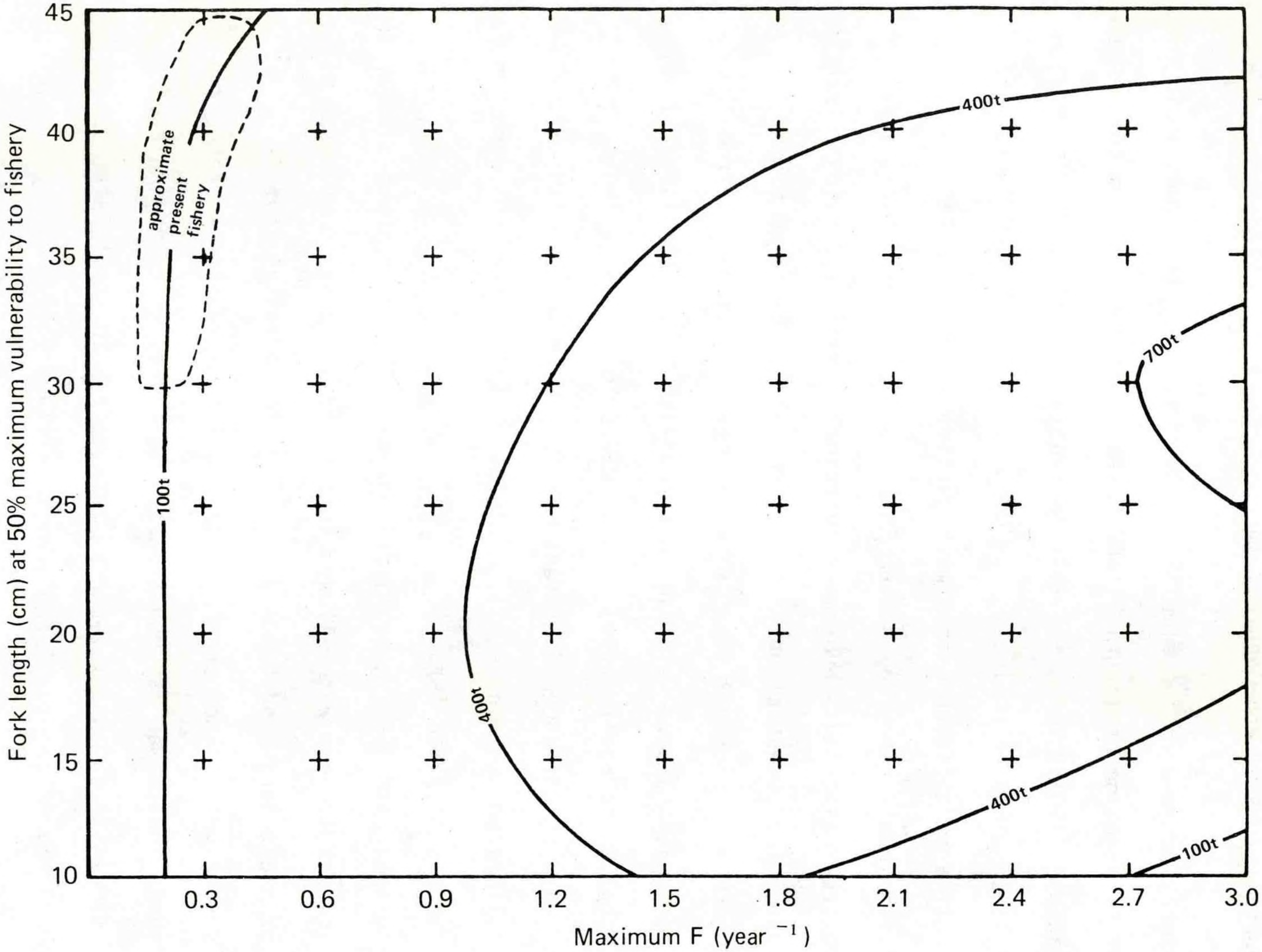

Figure 26.--Isopleths for average annual catch (t/100 km^2) of cannibalistic walleye pollock, based on data in Table 30.

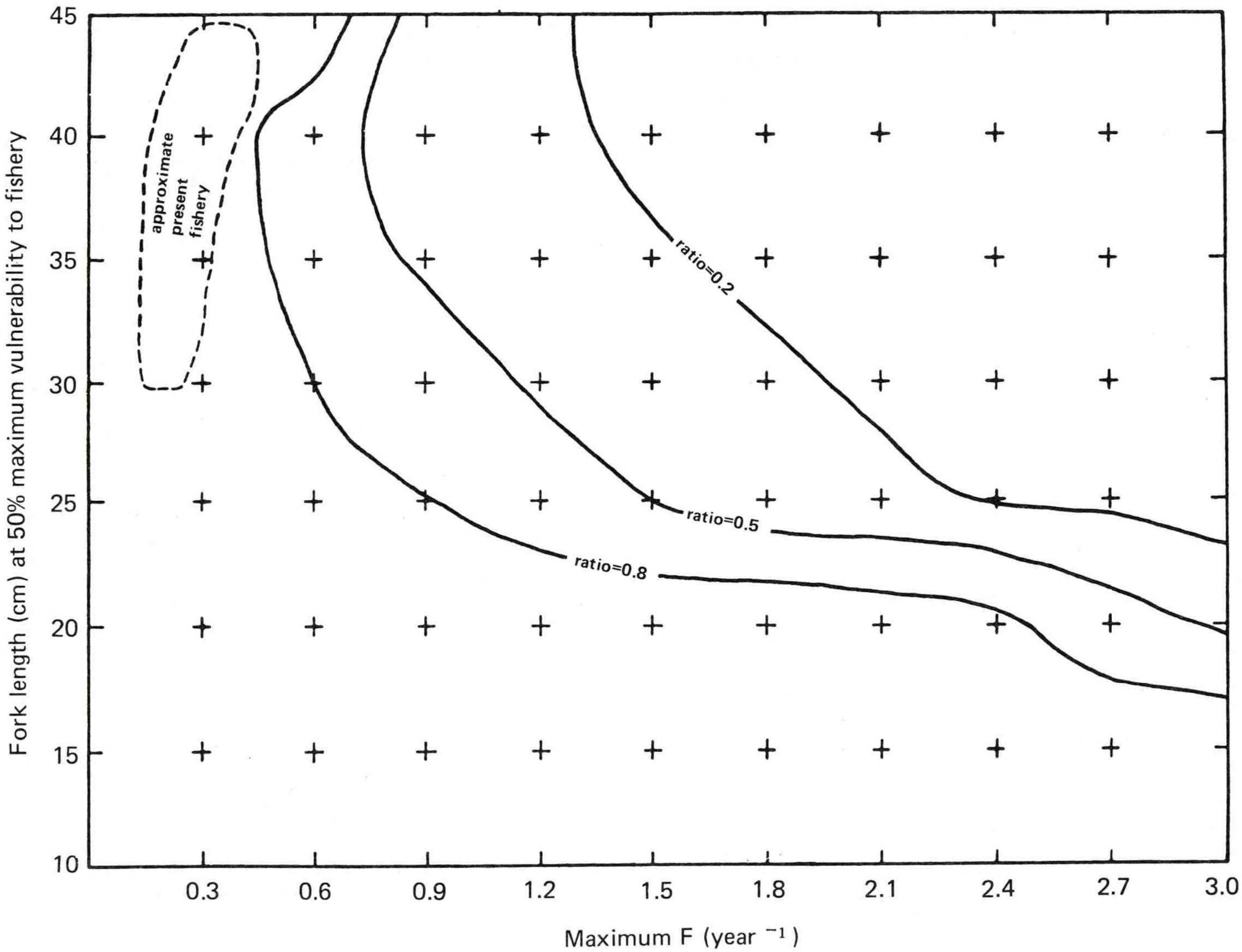

Figure 27.--Isopleths for catch variability (ratio of minimum annual catch to maximum annual catch) of cannibalistic walleye pollock, based on data in Table 36.

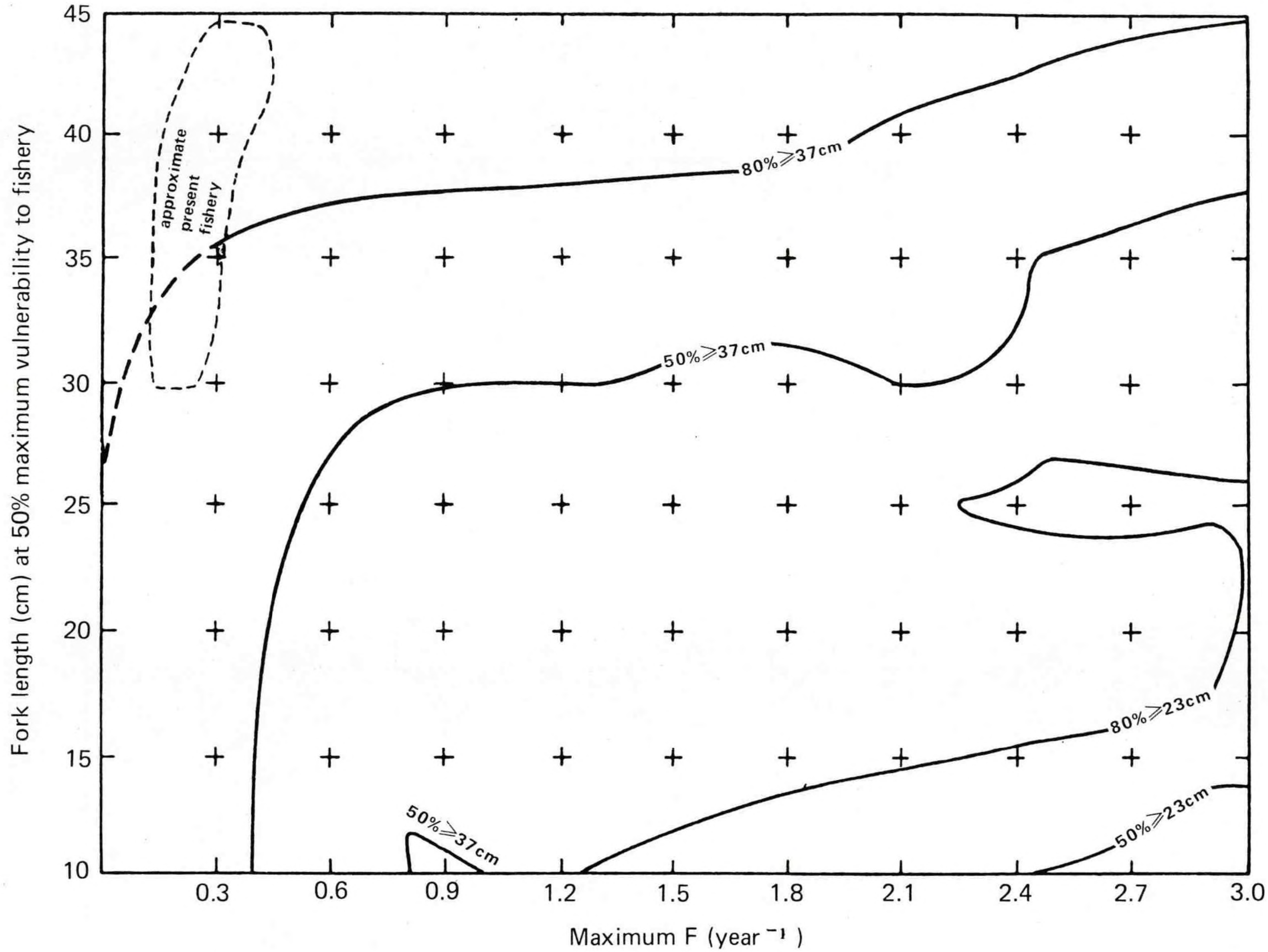

Figure 28.--Isopleths for average percentage of catch of cannibalistic walleye pollock on 13 May which exceeded 23 or 37 cm FL, based on data in Tables 32 and 34.

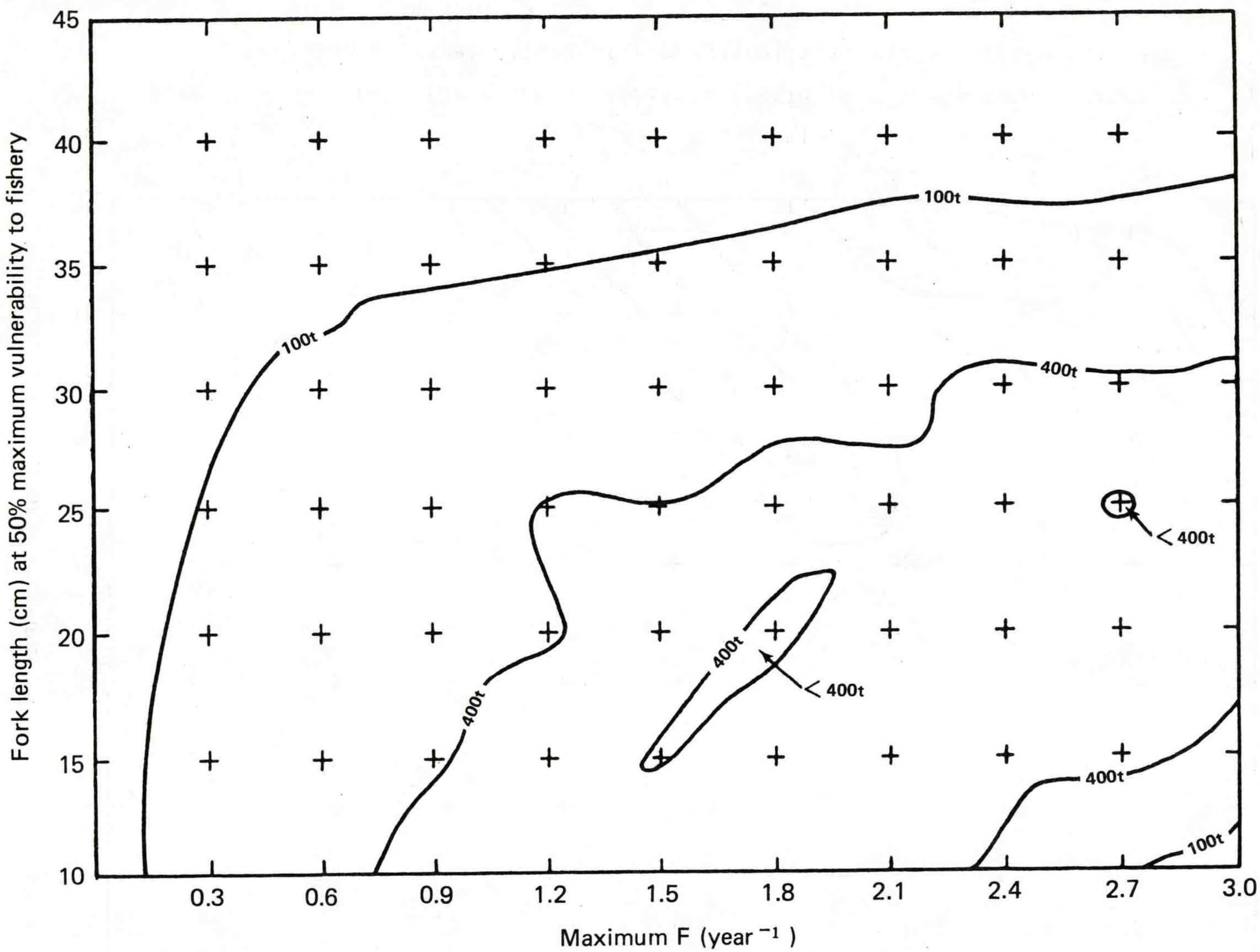

Figure 29.--Isopleths for average annual catch (t/100 km^2) of noncannibalistic walleye pollock, based on data in Table 31.

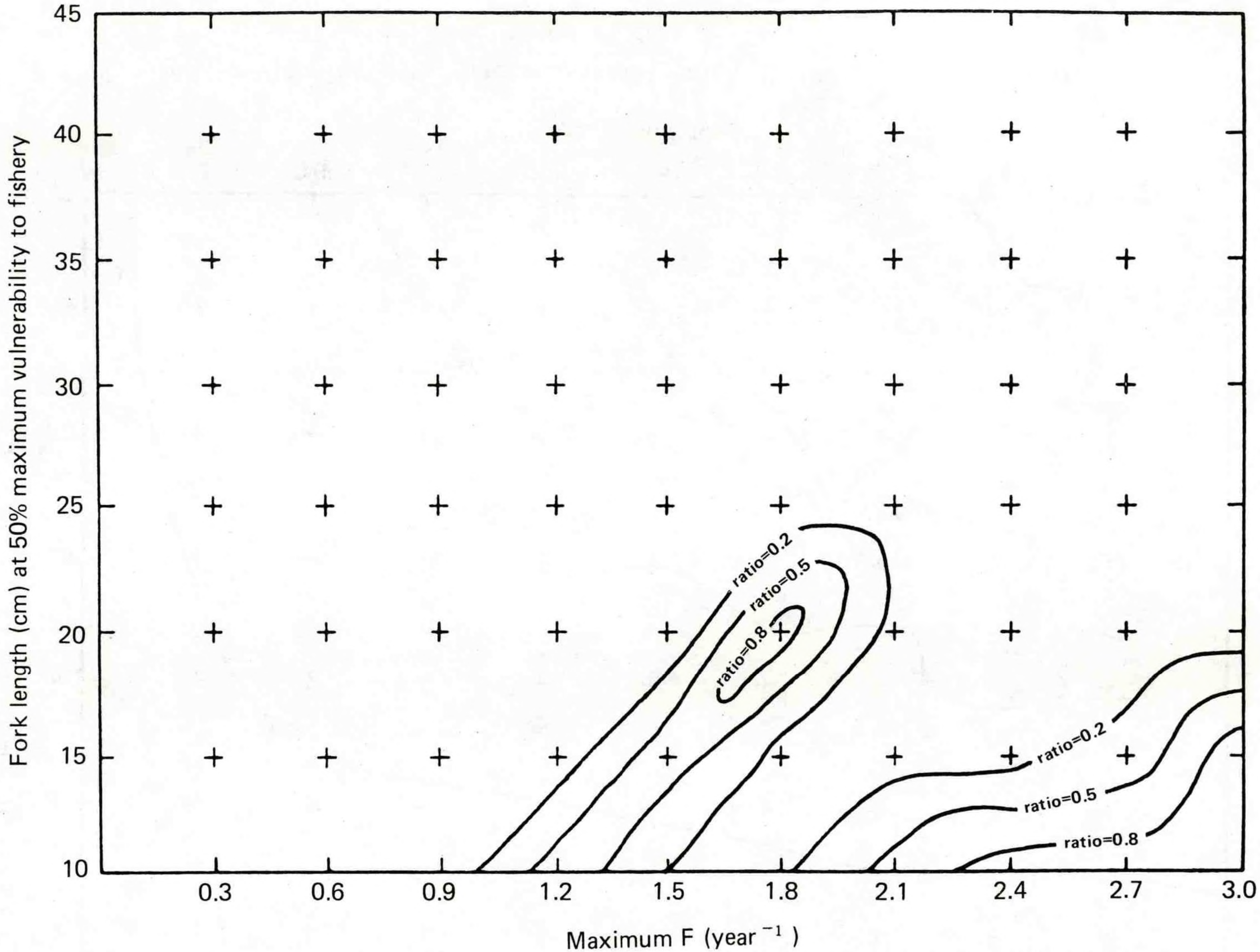

Figure 30.--Isopleths for catch variability (ratio of minimum annual catch to maximum annual catch) of noncannibalistic walleye pollock, based on data in Table 37.

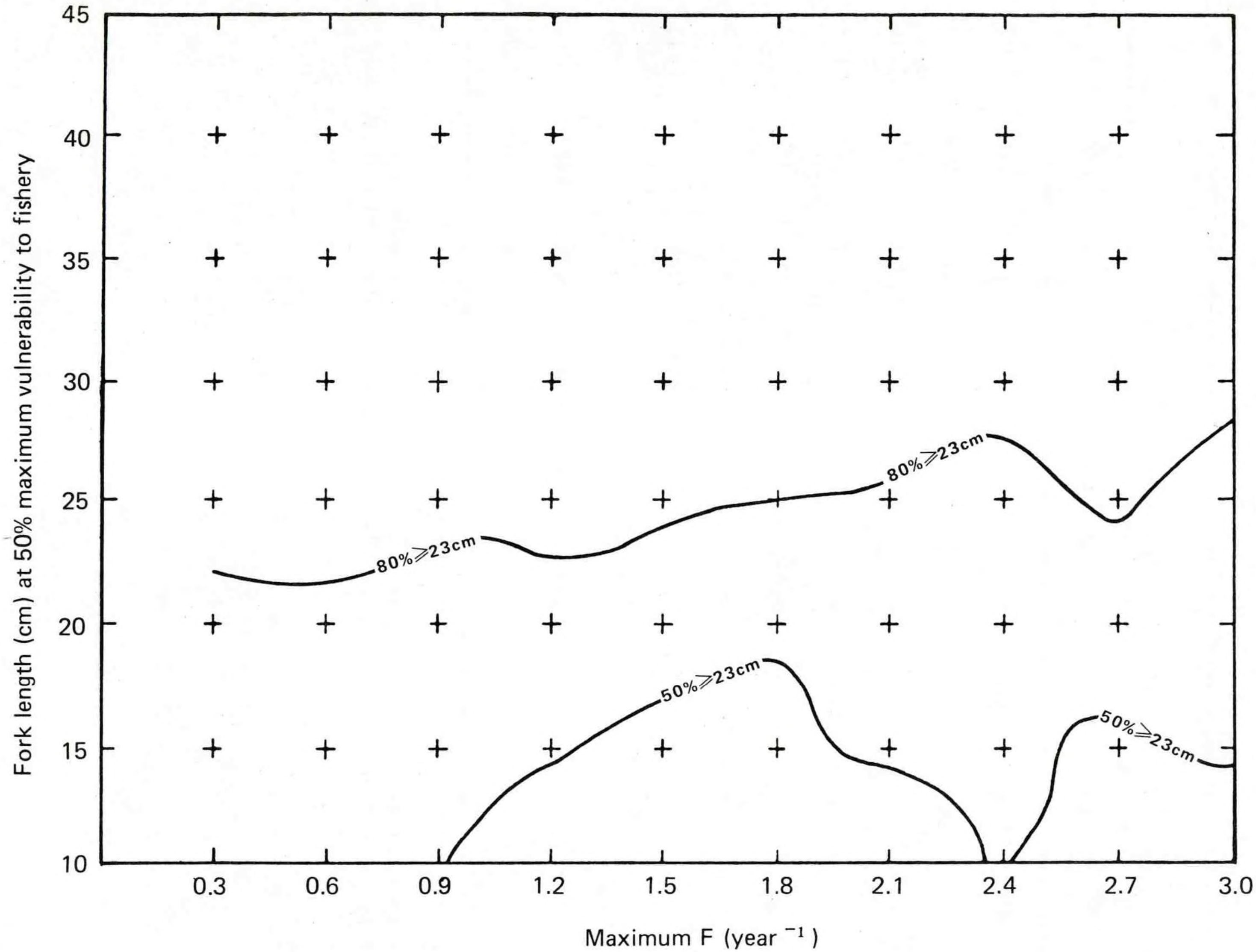

Figure 31.--Isopleths for average percentage of catch of noncannibalistic walleye pollock on 13 May which exceeded 23 or 37 cm FL, based on data in Tables 33 and 35.

Table 30.--Mean annual fishery catch (t/100 km^2) of cannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery). a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	159	162	163	160	153	138	114	80
0.6	261	274	282	277	262	229	179	122
0.9	328	359	380	369	344	300	235	139
1.2	378	428	456	438	404	359	284	172
1.5	410	479	516	488	460	418	331	197
1.8	408	510	555	529	515	481	372	220
2.1	357	511	569	581	592	549	412	241
2.4	246	472	564	635	642	606	455	256
2.7	97	396	537	676	700	655	481	264
3.0	0	283	495	709	733	681	502	278

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 31.--Mean annual fishery catch (t/100 km^2) of noncannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery). a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	237	211	151	115	78	28	6	1
0.6	353	301	275	236	140	48	10	3
0.9	465	379	339	294	228	69	16	3
1.2	498	507	386	419	235	90	25	5
1.5	604	380	482	400	303	108	30	5
1.8	536	523	361	453	363	127	33	6
2.1	518	507	552	438	353	171	38	8
2.4	335	504	543	492	469	147	45	8
2.7	100	491	554	390	428	174	36	10
3.0	0	340	501	539	456	207	48	9

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 32.--The average fraction, by weight, of the fishery catch of cannibalistic walleye pollock which were ≥23 cm fork length, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Values apply only to the date 13 May, not to an entire simulated year. a/

F	P_{84} (cm)							
($year^{-1}$)	10	15	20	25	30	35	40	45
0.3	0.947	0.979	0.997	1	1	1	1	1
0.6	0.904	0.962	0.995	1	1	1	1	1
0.9	0.853	0.940	0.992	0.999	1	1	1	1
1.2	0.795	0.913	0.988	0.999	1	1	1	1
1.5	0.733	0.883	0.984	0.999	1	1	1	1
1.8	0.668	0.851	0.979	0.918	0.979	0.997	1	1
2.1	0.598	0.817	0.974	0.822	0.980	0.996	0.999	1
2.4	0.515	0.782	0.969	0.774	0.915	0.994	0.998	1
2.7	0.421	0.739	0.964	0.754	0.934	0.991	0.996	1
3.0	0	0.678	0.775	0.772	0.920	0.987	0.995	1

a/ Averages were calculated from the last 201 yr of a 256-yr simulation. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 33.--The average fraction, by weight, of the fishery catch of noncannibalistic walleye pollock which were $\geq$23 cm fork length, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Values apply only to the date 13 May, not to an entire simulated year. a/

F	P_{84} (cm)							
(year^{-1})	10	15	20	25	30	35	40	45
0.3	0.618	0.653	0.770	0.851	0.946	0.906	0.926	0.968
0.6	0.550	0.652	0.781	0.858	0.925	0.914	0.923	0.928
0.9	0.522	0.639	0.759	0.829	0.905	0.944	0.931	0.948
1.2	0.339	0.548	0.746	0.850	0.929	0.944	0.937	0.952
1.5	0.381	0.418	0.666	0.838	0.889	0.950	0.931	0.953
1.8	0.475	0.483	0.509	0.810	0.899	0.919	0.908	0.906
2.1	0.422	0.529	0.582	0.789	0.881	0.938	0.903	0.935
2.4	0.510	0.562	0.633	0.742	0.872	0.991	0.953	0.914
2.7	0.417	0.442	0.676	0.834	0.849	0.946	0.906	0.933
3.0	0.000	0.675	0.707	0.709	0.859	0.922	0.920	0.945

a/ Averages were calculated from the last 201 yr of a 256-yr simulation. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 34.--The average fraction, by weight, of the fishery catch of cannibalistic walleye pollock which were ≥37 cm fork length, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Values apply only to the date 13 May, not to an entire simulated year. a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	0.548	0.563	0.577	0.617	0.682	0.782	0.944	0.992
0.6	0.392	0.405	0.415	0.463	0.545	0.684	0.914	0.988
0.9	0.548	0.282	0.287	0.335	0.511	0.688	0.910	0.981
1.2	0.427	0.183	0.190	0.277	0.519	0.656	0.893	0.977
1.5	0.322	0.111	0.119	0.291	0.472	0.635	0.878	0.972
1.8	0.235	0.066	0.072	0.281	0.443	0.633	0.864	0.966
2.1	0.166	0.210	0.042	0.254	0.512	0.567	0.753	0.957
2.4	0.109	0.156	0.025	0.229	0.485	0.505	0.638	0.951
2.7	0.065	0.113	0.092	0.198	0.377	0.457	0.614	0.842
3.0	0.000	0.079	0.112	0.161	0.326	0.406	0.580	0.805

a/ Averages were calculated from the last 201 yr of a 256-yr simulation. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 35.--The average fraction, by weight, of the fishery catch of noncannibalistic walleye pollock which were ≥37 cm fork length, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Values apply only to the date 13 May, not to an entire simulated year.[a]

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	0.106	0.118	0.162	0.213	0.221	0.307	0.418	0.493
0.6	0.093	0.125	0.178	0.163	0.239	0.310	0.383	0.423
0.9	0.098	0.140	0.183	0.187	0.202	0.321	0.412	0.449
1.2	0.038	0.087	0.183	0.163	0.222	0.275	0.400	0.399
1.5	0.043	0.027	0.124	0.171	0.168	0.305	0.379	0.412
1.8	0.102	0.084	0.028	0.186	0.153	0.267	0.345	0.405
2.1	0.079	0.123	0.130	0.088	0.208	0.290	0.333	0.375
2.4	0.097	0.123	0.119	0.145	0.182	0.300	0.340	0.374
2.7	0.061	0.100	0.137	0.090	0.153	0.242	0.357	0.383
3.0	0.000	0.072	0.134	0.228	0.165	0.227	0.313	0.384

[a] Averages were calculated from the last 201 yr of a 256-yr simulation. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 36.--Ratio of the minimum annual fishery catch of cannibalistic walleye pollock to the maximum, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). a/

F (year^{-1})	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	1	1	0.986	1	1	1	1	1
0.6	1	1	1	1	0.802	0.666	0.606	1
0.9	1	1	1	0.799	0.586	0.437	0.373	0.350
1.2	1	1	1	0.669	0.477	0.323	0.238	0.226
1.5	1	1	1	0.489	0.339	0.223	0.153	0.154
1.8	1	1	1	0.345	0.235	0.149	0.098	0.097
2.1	1	1	1	0.248	0.162	0.097	0.065	0.073
2.4	1	1	0.884	0.175	0.126	0.066	0.044	0.049
2.7	1	1	0.610	0.145	0.075	0.044	0.031	0.027
3.0	1	1	0.417	0.152	0.065	0.036	0.018	0.019

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 37.--Ratio of the minimum annual fishery catch of noncannibalistic walleye pollock to the maximum, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0	0
1.2	0.682	0.008	0	0	0	0	0	0
1.5	0.163	0.672	0	0	0	0	0	0
1.8	0.158	0.097	0.999	0	0	0	0	0
2.1	0.616	0.047	0.023	0	0	0	0	0
2.4	1	0.065	0.002	0	0	0	0	0
2.7	1	0.280	0.020	0	0	0	0	0
3.0	1	1	0.022	0	0	0	0	0

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.0005) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 38.--Minimum annual fishery catch (t/100 km^2) of cannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery). a/

F (year^{-1})	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	159	162	162	160	153	138	114	80
0.6	261	274	282	277	233	185	136	122
0.9	328	359	380	328	256	192	134	75
1.2	378	428	456	352	266	196	121	72
1.5	410	479	516	322	239	186	104	63
1.8	408	510	555	286	205	169	89	48
2.1	357	511	569	253	170	149	77	42
2.4	246	472	529	217	149	124	61	32
2.7	97	396	411	197	139	93	45	19
3.0	0	283	302	202	132	82	31	15

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 39.--Minimum annual fishery catch (t/100 km^2) of noncannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery). a/

F (year^{-1})	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0	0
1.2	404	9	0	0	0	0	0	0
1.5	152	306	0	0	0	0	0	0
1.8	124	87	361	0	0	0	0	0
2.1	403	47	31	0	0	0	0	0
2.4	335	58	2	0	0	0	0	0
2.7	100	207	25	0	0	0	0	0
3.0	0	340	26	0	0	0	0	0

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 40.--Maximum annual fishery catch (t/100 km^2) of cannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery).[a/]

F (year^{-1})	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	159	162	164	160	153	138	114	80
0.6	261	274	282	277	291	278	225	122
0.9	328	359	380	410	436	441	361	215
1.2	378	428	456	525	558	605	510	317
1.5	410	479	516	659	707	834	680	409
1.8	408	510	555	829	873	1,133	906	498
2.1	357	511	569	1,021	1,051	1,535	1,176	578
2.4	246	472	599	1,239	1,182	1,886	1,393	656
2.7	97	396	674	1,356	1,853	2,117	1,445	716
3.0	0	283	723	1,325	2,041	2,309	1,692	767

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 41.--Maximum annual fishery catch (t/100 km^2) of noncannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to fishery). a/

F ($year^{-1}$)	P_{84} (cm) 10	15	20	25	30	35	40	45
0.3	763	682	676	684	526	261	92	13
0.6	1,106	1,035	1,001	1,010	886	483	175	41
0.9	1,180	1,092	1,191	1,261	1,227	672	196	61
1.2	593	1,108	1,266	1,480	1,455	791	290	58
1.5	938	455	1,324	1,600	1,650	998	379	36
1.8	787	895	361	1,705	1,815	1,103	374	114
2.1	655	982	1,344	1,529	1,953	1,262	326	125
2.4	335	892	1,289	1,770	1,969	1,053	521	140
2.7	100	742	1,266	1,792	1,932	1,566	354	118
3.0	0	340	1,189	1,837	2,136	1,433	701	156

a/ Values were calculated from the last 201 yr of a 256-yr simulation. Small values (<0.5 t/100 km^2) were rounded to 0. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 42.--Dominant period (years) of fluctuations in annual fishery catches of cannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	1	1	8.04	1	1	1	1	1
0.6	1	1	1	1	6.28	6.28	6.70	1
0.9	1	1	1	5.91	5.91	6.09	6.48	6.93
1.2	1	1	1	5.43	5.43	5.91	6.48	7.18
1.5	1	1	1	5.15	5.29	5.74	6.48	7.18
1.8	1	1	1	4.90	5.02	5.43	6.28	7.44
2.1	1	1	1	4.67	5.02	5.43	6.28	7.44
2.4	1	1	4.10	4.47	5.02	5.43	6.48	7.44
2.7	1	1	3.86	4.28	4.79	5.58	6.93	7.73
3.0	1	1	3.59	4.02	4.67	5.58	6.93	7.73

a/ The dominant period corresponded to the maximum ordinate of a periodogram calculated from the last 201 yr of a 256-yr simulation. However, a dominant period of 1 yr means that stationary conditions occurred, so that the simulation was stopped before 256 yr had elapsed. Other possible periods were 2.01-201 yr. If periods <2.00 yr existed in the data, then aliasing occurred. Relative vulnerability to cannibalism, P_5, equaled 1.

Table 43.--Dominant period (years) of fluctuations in annual fishery catches of noncannibalistic walleye pollock, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.3	14.36	14.36	11.82	15.46	14.36	7.44	2.01	4.10
0.6	16.75	14.36	14.36	18.27	13.40	10.05	2.18	2.61
0.9	12.56	10.58	10.58	13.40	4.37	13.40	2.68	6.93
1.2	2.01	5.74	7.73	20.10	16.75	14.36	2.58	18.27
1.5	10.58	2.01	22.33	13.40	5.02	15.46	2.03	4.19
1.8	8.38	4.79	201.0	28.71	4.79	22.33	6.70	2.75
2.1	3.35	5.02	5.15	22.33	6.48	16.75	2.05	2.75
2.4	1	3.65	4.37	20.10	4.67	15.46	2.34	9.57
2.7	1	3.19	4.02	28.71	20.10	16.75	15.46	8.04
3.0	1	1	3.59	5.91	25.13	3.00	11.82	6.09

a/ The dominant period corresponded to the maximum ordinate of a periodogram calculated from the last 201 yr of a 256-yr simulation. However, a dominant period of 1 yr means that stationary conditions occurred, so that the simulation was stopped before 256 yr had elapsed. Other possible periods were 2.01-201 yr. If periods <2.00 yr existed in the data, then aliasing occurred. Relative vulnerability to cannibalism, P_5, equaled 0.

Table 44.--Number of normalized periodogram ordinates greater than the critical value 0.02951, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Periodograms were calculated from annual fishery catches of cannibalistic walleye pollock. A dash (-) indicates no periodogram was calculated because stationary conditions occurred. a/

F	P_{84} (cm)							
(year^{-1})	10	15	20	25	30	35	40	45
0.3	-	-	1	-	-	-	-	-
0.6	-	-	-	-	1	4	4	-
0.9	-	-	-	2	4	1	1	1
1.2	-	-	-	2	4	1	2	2
1.5	-	-	-	1	1	2	3	2
1.8	-	-	-	1	1	5	5	2
2.1	-	-	-	1	2	5	4	3
2.4	-	-	4	2	2	5	2	3
2.7	-	-	1	2	5	2	5	4
3.0	-	-	1	3	3	5	6	2

a/ The value 0.02951 is the critical value (equal to lambda x g_F, where lambda = 0.4 and g_F = 0.07378) used in the T_{lambda} test of Siegel (1980:equation 3.1). This statistical test was used to determine whether a time series was white noise or harmonic at the 95% significance level. All time series described in this table can be considered harmonic. The time series in which stationary conditions occurred were harmonic with a fundamental period of 1 yr. The null hypothesis of white noise was rejected at the 95% level for the other time series using Siegel's test. Relative vulnerability to cannibalism, P_5, equaled 1. Data values were calculated from the last 201 yr of a 256-yr simulation.

Table 45.--Number of normalized periodogram ordinates greater than the critical value 0.02951, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery). Periodograms were calculated from annual fishery catches of noncannibalistic walleye pollock. A dash (-) indicates no periodogram was calculated because stationary conditions occurred. a/

F	P_{84} (cm)							
($year^{-1}$)	10	15	20	25	30	35	40	45
0.3	7b/	7b/	6b/	8b/	9b/	6b/	4	6
0.6	6b/	7b/	12b/	11b/	6b/	6	4	3
0.9	13b/	10b/	10b/	7b/	6	6	8	5
1.2	3b/	10b/	8b/	12b/	7b/	2	5	4
1.5	10b/	3b/	13b/	12b/	9b/	5b/	5	6
1.8	7b/	6b/	10b/	9b/	7	4	6	6
2.1	2b/	6b/	9b/	2b/	10b/	6	6b/	7
2.4	-	8b/	10b/	9b/	8b/	8b/	4	6b/
2.7	-	2b/	9b/	4b/	5b/	7	7	3
3.0	-	-	9b/	9b/	7b/	7	2	9

a/ The value 0.02951 is the critical value (equal to lambda x g_F, where lambda = 0.4 and g_F = 0.07378) used in the T_{lambda} test of Siegel (1980: equation 3.1). This statistical test was used to determine whether a time series was white noise or harmonic at the 95% significance level. Relative vulnerability to cannibalism, P_5, equaled 0. Data values were calculated from the last 201 yr of a 256-yr simulation.

b/ Time series for which the null hypothesis of white noise was rejected at the 95% level using Siegel's T_{lambda} test. These time series can therefore be considered harmonic. The simulations in which stationary conditions occurred were also harmonic with a fundamental period of 1 yr.

calculated by linear interpolation along grid lines using data in Tables 30-37; these data points were connected by hand to form the isopleths. If stationary conditions occurred in a simulation, only the last year of the simulation was used; but if stationary conditions did not occur, the last 201 data points (simulated years 56-256) were used. This was to allow initial transient fluctuations to fade away.

4.3.1. Possible Optimum Yields with Cannibalism

Whenever an attempt is made to determine an optimum, criteria must (implicitly or explicitly) be determined to measure the optimum. These criteria are generally an expression of the values of the persons determining the optimum. Because of this, "the optimum fishery yield of pollock" is not determined in this study. Instead, several different possible simulated optimums are pointed out, with discussion of their merit according to the following criteria:

1) long-term average annual catch;
2) amount of variation in annual catches;
3) risk of a long-term stock crash;
4) amount of fishing effort required; and
5) desired amounts and kinds of market products.

The simulations with cannibalism (P_5=1) were thought to most closely represent the actual eastern Bering Sea pollock population, so the possible optimums discussed in Sections 4.3.1.1 to 4.3.1.3 are based on simulations which used this value. Actual constraints on the maximum value of F were not estimated for this study. Instead a value of F=3.0 $year^{-1}$ was used, which is approximately 10 times the value resulting from the present fishery.

4.3.1.1. Maximization of Average Catch Allowing Large Fluctuations--Considering the final 201 yr of each simulation, the maximum average simulated annual pollock catch for P_5=1 and F$\leq$3.0 year^{-1} was 733 t/100 km^2. This occurred for F=3.0 year^{-1} and P_{84}=30 cm (Table 30). However, the annual catch calculated using these parameters did not become stationary, but instead varied widely--the minimum annual catch was only 6.5% of the maximum annual catch for this combination of parameters (Table 36). Because of this wide variation, this combination of parameters might not be considered to be optimum despite the fact that it resulted in an average annual yield more than six times the annual yield of the approximate "present" fishery of 114 t/100 km^2, where F=0.3 year^{-1} and P_{84}=40 cm. In addition, these wide fluctuations might indicate that the risk of a longer term stock crash would be quite high if the stock was so heavily exploited, perhaps as a result of unexpected stochastic environmental fluctuations or resource competition with other species. However, the present implementation of POL was not designed to assess potential effects of stochastic environmental fluctuations or competition with other species, although it can be used to predict consequences of deterministic fluctuations in food supply. The model could be easily modified to include stochastic fluctuations in food supply by using stochastic variation in the primary production driving function or in the plankton mortality parameters which represent mortality not otherwise accounted for (P_{39}, P_{47}, P_{57}).

Further increases in simulated average annual catches of pollock also resulted for F>3.0. A future study may explore whether such large values of F are economically feasible.

4.3.1.2. Maximization of Average Catch Avoiding Large Fluctuations--With the constraint on variation that the minimum annual catch be at least 80% of the maximum annual catch, for $F \leq 3.0$ year^{-1} the maximum average annual catch (for the final 201 simulated yr) was 569 t/100 km^2. This occurred for F=2.1 year^{-1} and P_{84}=20 cm (Tables 30 and 36). No starvation mortality occurred for pollock in this case after the occurrence of stationary conditions. In such a fishery, care would have to be taken to catch a sufficient amount of small pollock, or wide fluctuations could still result. For example, with only a small increase in length at 50% maximum vulnerability to the fishery, so that P_{84}=25 cm and F=2.1 year^{-1}, the minimum annual catch was only 24.8% of the maximum annual catch (Table 36). Some margin for error would be necessary because of uncertainties which could arise from underreporting, unavoidable measurement error, environmental variation, or other sources. Size selectivity and fishing mortality rates can presumably only be imprecisely controlled, at best, in a large fishery such as the pollock trawl fishery.

Further increases in F to greater than 3.0 year^{-1} could result in average catches greater than 569 t/100 km^2 without large annual fluctuations. This possibility may be explored in future simulation experiments.

4.3.1.3. Maximization of Catch for "Existing" Value of F--With the constraint that F be equal to its approximate value in the present fishery (about 0.3 year^{-1}), the maximum long-term annual yield, about 163 t/100 km^2, occurred for P_{84}=20 cm (Table 30). In addition, this combination of parameters (P_{84}=20 cm, F=0.3 year^{-1}) seems to be further away from the zone of fishery induced variation (Figure 27) than the parameter values thought to apply to the present fishery (P_{84}=40 cm, F=0.3 year^{-1}). This suggests that the biomass of pollock caught might be increased without increasing present effort levels, and variation in the size of annual pollock catches might be reduced, if net mesh size was decreased or if there was a greater emphasis on targeting smaller pollock in fishing operations.

4.3.2. Constraints on Optimum Yield Caused by Size of Individual Pollock

A factor in the determination of an optimum yield of pollock is the size of pollock required to economically produce a given product (Wespestad and Terry in press). Two major products made from pollock are surimi (a type of fish paste) and fish fillets. The production (measured by weight) of surimi or fish fillets from a pollock is approximately proportional to its body weight (Natural Resources Consultants 1981:46-47, 87). Based on this, the total production of surimi or fillets is approximately proportional to the weight of the pollock catch used to make each product. An approximate minimum size of pollock used for surimi is 23 cm FL (e.g., Wall 1978). An approximate minimum size of pollock used in filleting machinery is 37 cm (e.g., Korson and Conradus 1981:42). Simulated annual catches of pollock over 23 and 37 cm were not recorded in this study, but may be determined in a future study. However, preliminary indications of the importance of these minimum size constraints for pollock can be determined from Tables 32 and 34. The fraction (by weight) of the derivative of the cumulative annual pollock catch (variable YLD') on the date 13 May consisting of pollock over 23 or 37 cm FL was calculated for simulated years 56-256. The average of these fractions was used in Tables 32 and 34 unless stationary conditions occurred, in which case only the value calculated for the last year simulated was used. For most values of F and P_{84}

(including the ones likely to be considered optimum), on the average more than 80% (by weight) of the simulated catches taken on 13 May consisted of pollock $\geq$23 cm FL (Table 32). This is a preliminary indication that this lower size limit might not greatly affect the choice of an optimum yield of pollock. In contrast, for most values of F and P_{84}, on the average less than 80% of the simulated catches taken on 13 May consisted of pollock $\geq$37 cm FL (Table 34). Consequently, minimum size requirements for fish could be an important constraint on the values of F and P_{84} chosen to produce an optimum yield of pollock to be used largely for fillets. This may be studied more rigorously in the future.

4.3.3. Some Causes of Persistent Catch Fluctuations with Cannibalism

An interesting question is, "What were the causes of the large, persistent catch fluctuations which occurred with cannibalism (P_5=1) for various combinations of F and P_{84}?" To provide a partial answer, the parameter values F=3.0 year^{-1} and P_{84}=30 cm were chosen, and a 256-yr simulation run was performed. Below is a detailed examination of the phenomena, particularly the age structure, which accompanied the catch fluctuation during simulated years 250-256 (Figure 32). These same phenomena may be typical of the circumstances resulting in fluctuations for other combinations of F and P_{84} with P_5=1.

Annual catches during years 250-256 were harvested from pollock biomasses which existed from 13 May, year 249, to 13 May, year 256. Figures 33-39 show

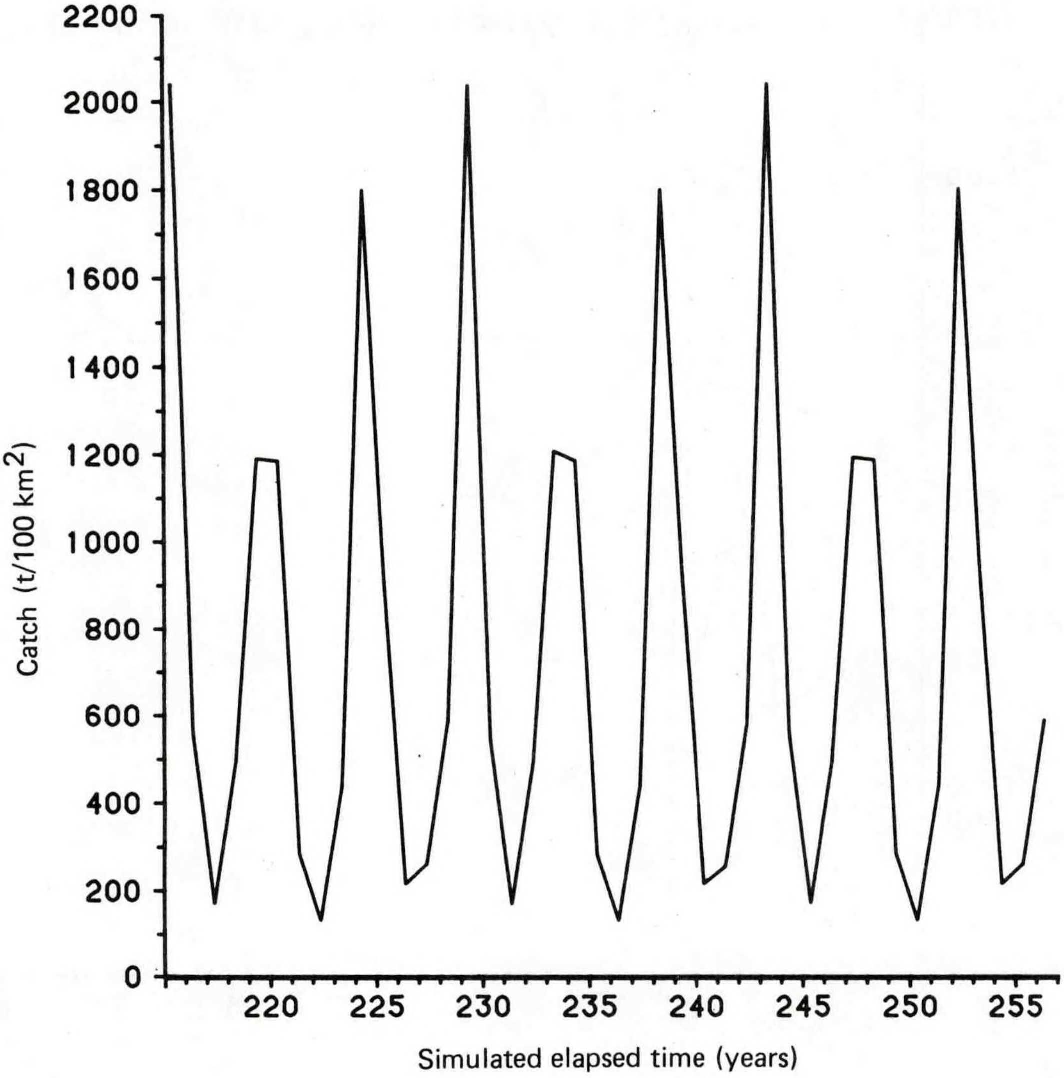

Figure 32.--Annual catch of walleye pollock for years ending on 13 May. Simulation parameters used were P_5=1 (cannibalism allowed), F=3.0 year^{-1}, and P_{84}=30 cm (=length at 50% maximum vulnerability to fishery).

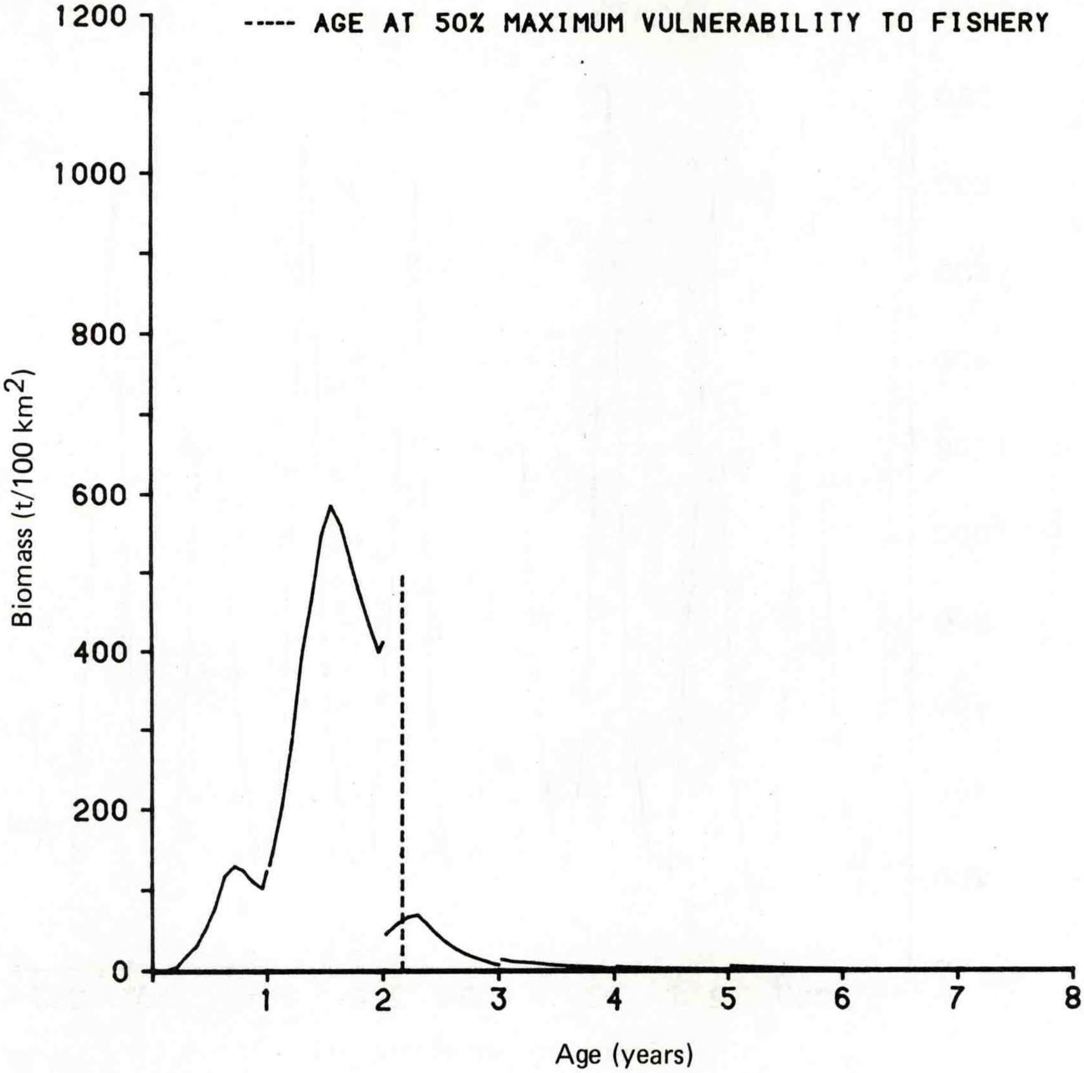

Figure 33.--Walleye pollock biomass-at-age (simulated year 249-250). The annual catch at the end of the year (on 13 May) was 133 t/100 km^2.

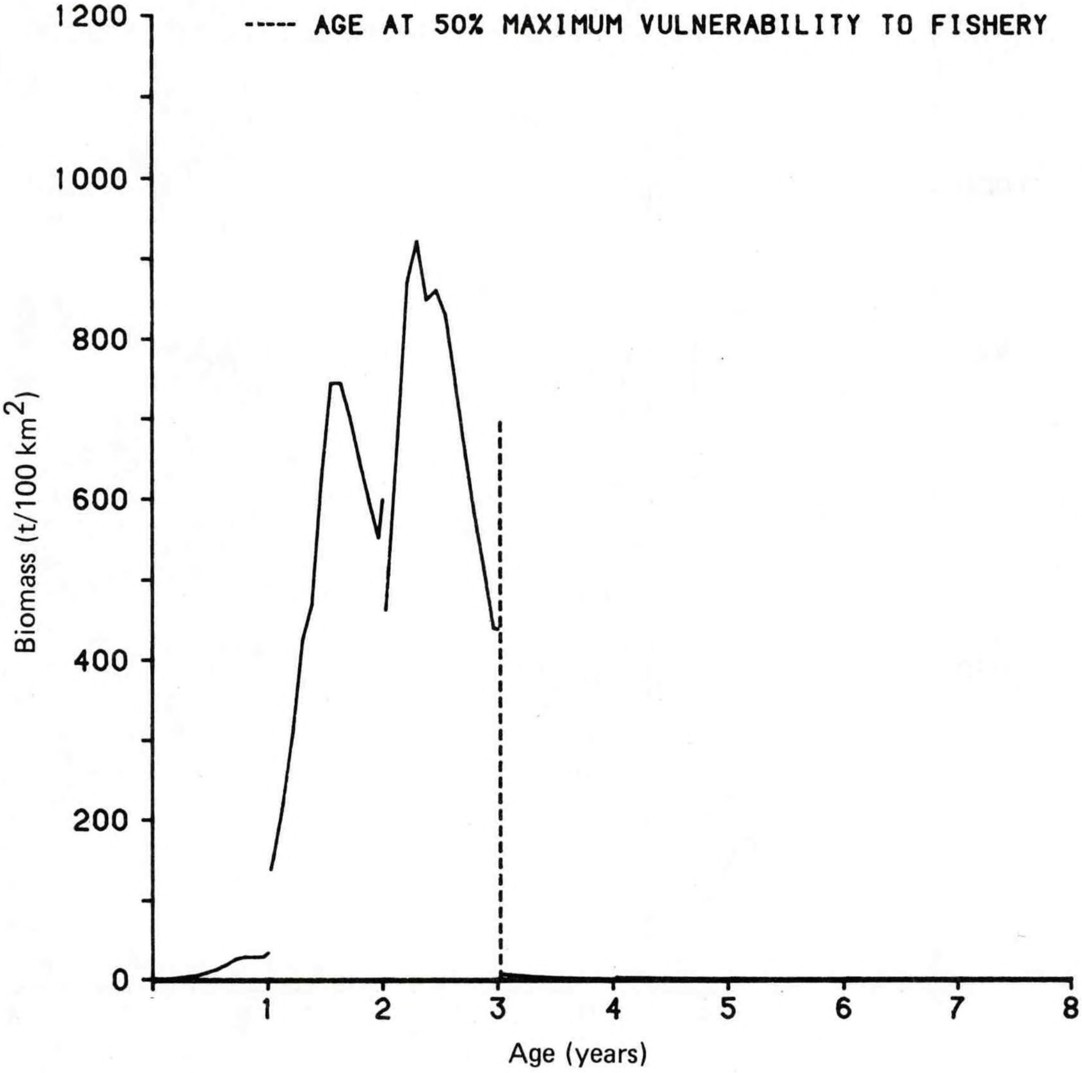

Figure 34.--Walleye pollock biomass-at-age (simulated year 250-251). The annual catch at the end of the year (on 13 May) was 438 t/100 km^2.

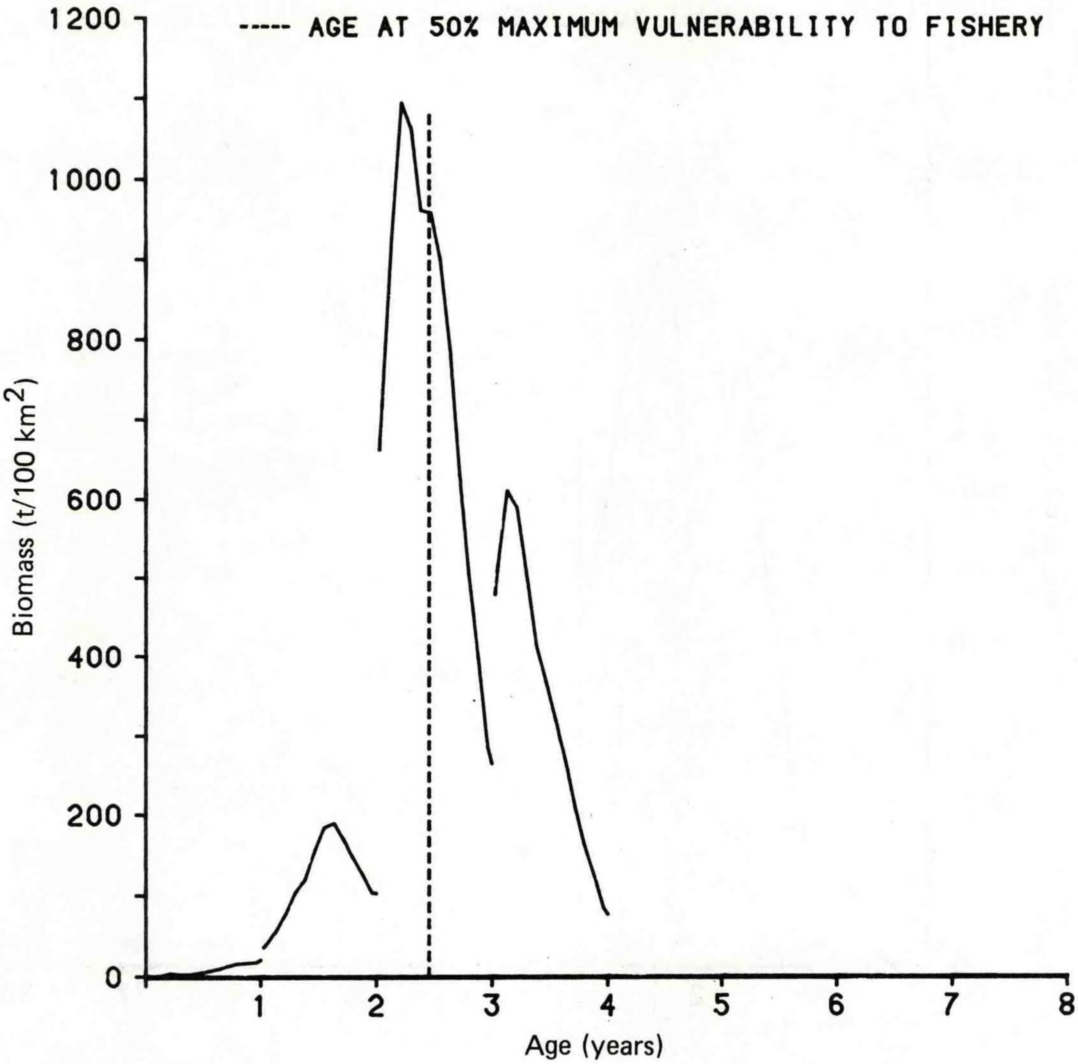

Figure 35.--Walleye pollock biomass-at-age (simulated year 251-252). The annual catch at the end of the year (on 13 May) was 1800 t/100 km^2.

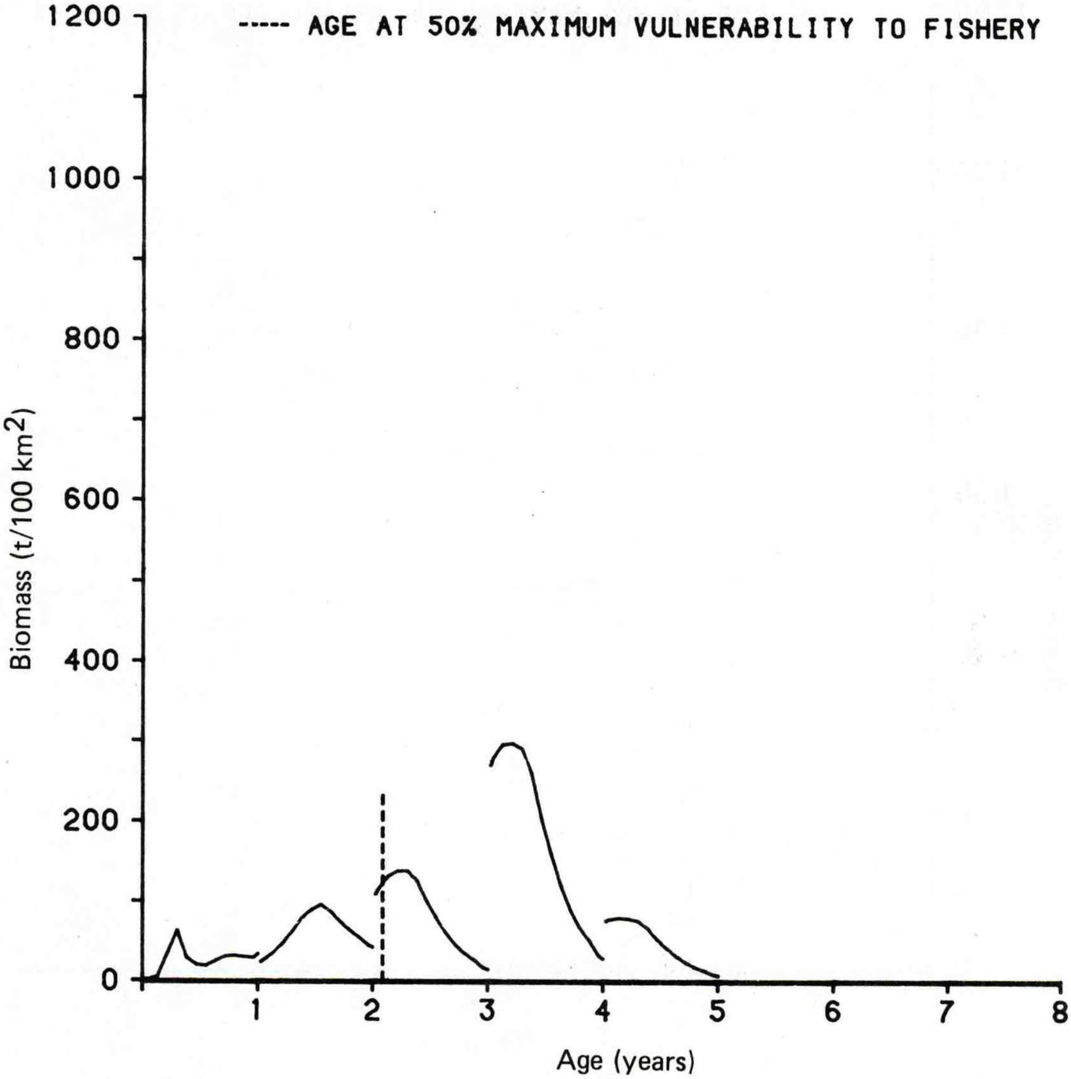

Figure 36.--Walleye pollock biomass-at-age (simulated year 252-253). The annual catch at the end of the year (on 13 May) was 907 t/100 km^2.

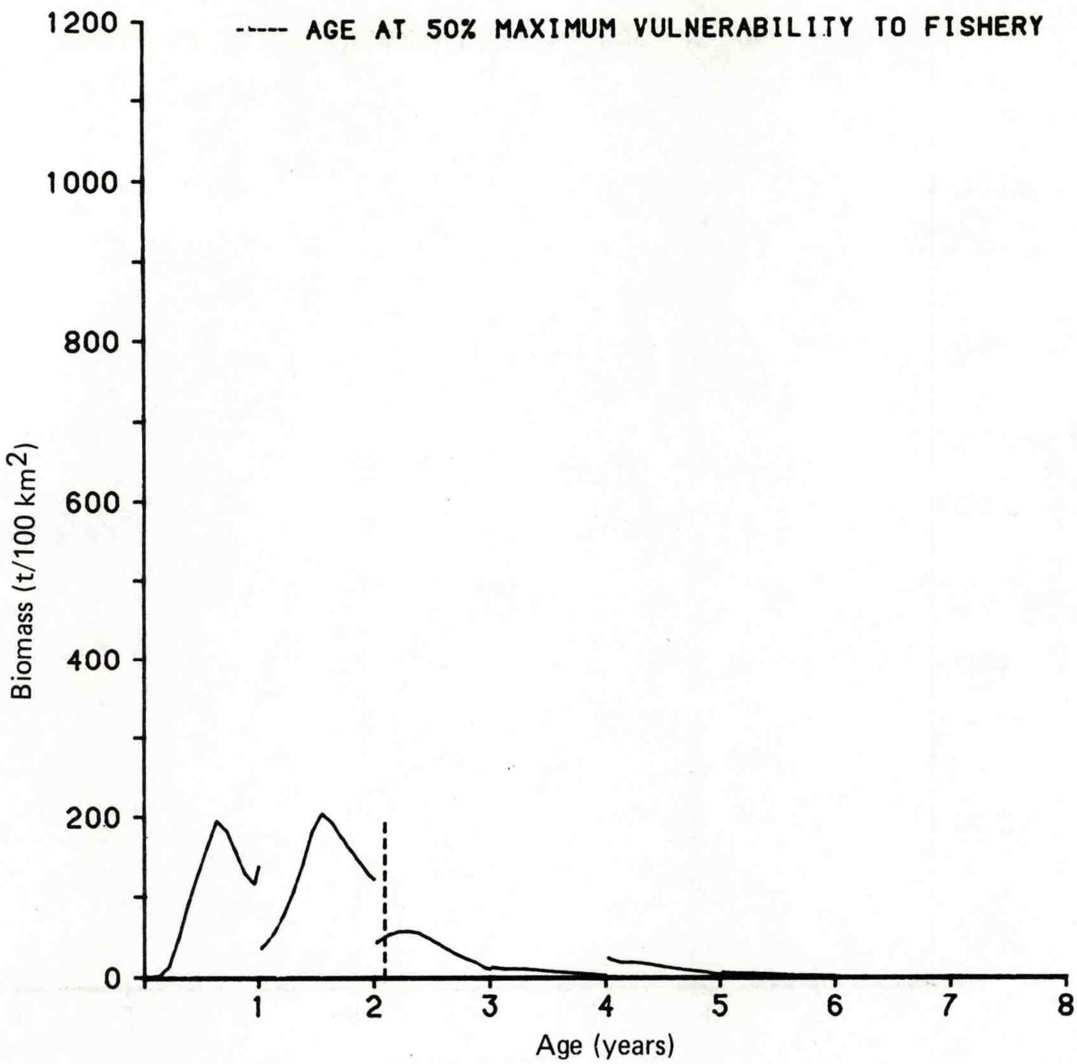

Figure 37.--Walleye pollock biomass-at-age (simulated year 253-254). The annual catch at the end of the year (on 13 May) was 215 t/100 km^2.

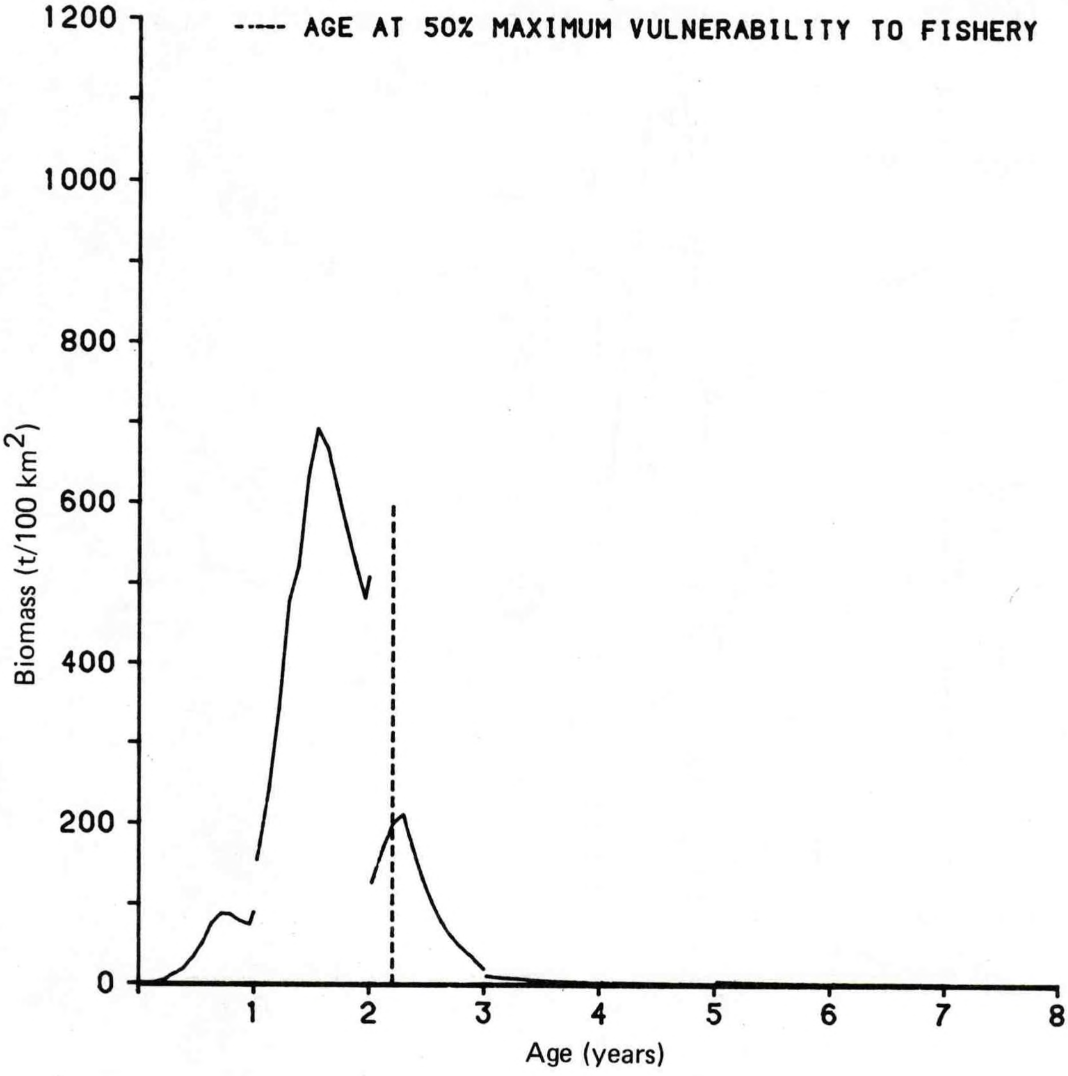

Figure 38.--Walleye pollock biomass-at-age (simulated year 254-255). The annual catch at the end of the year (on 13 May) was 261 t/100 km^2.

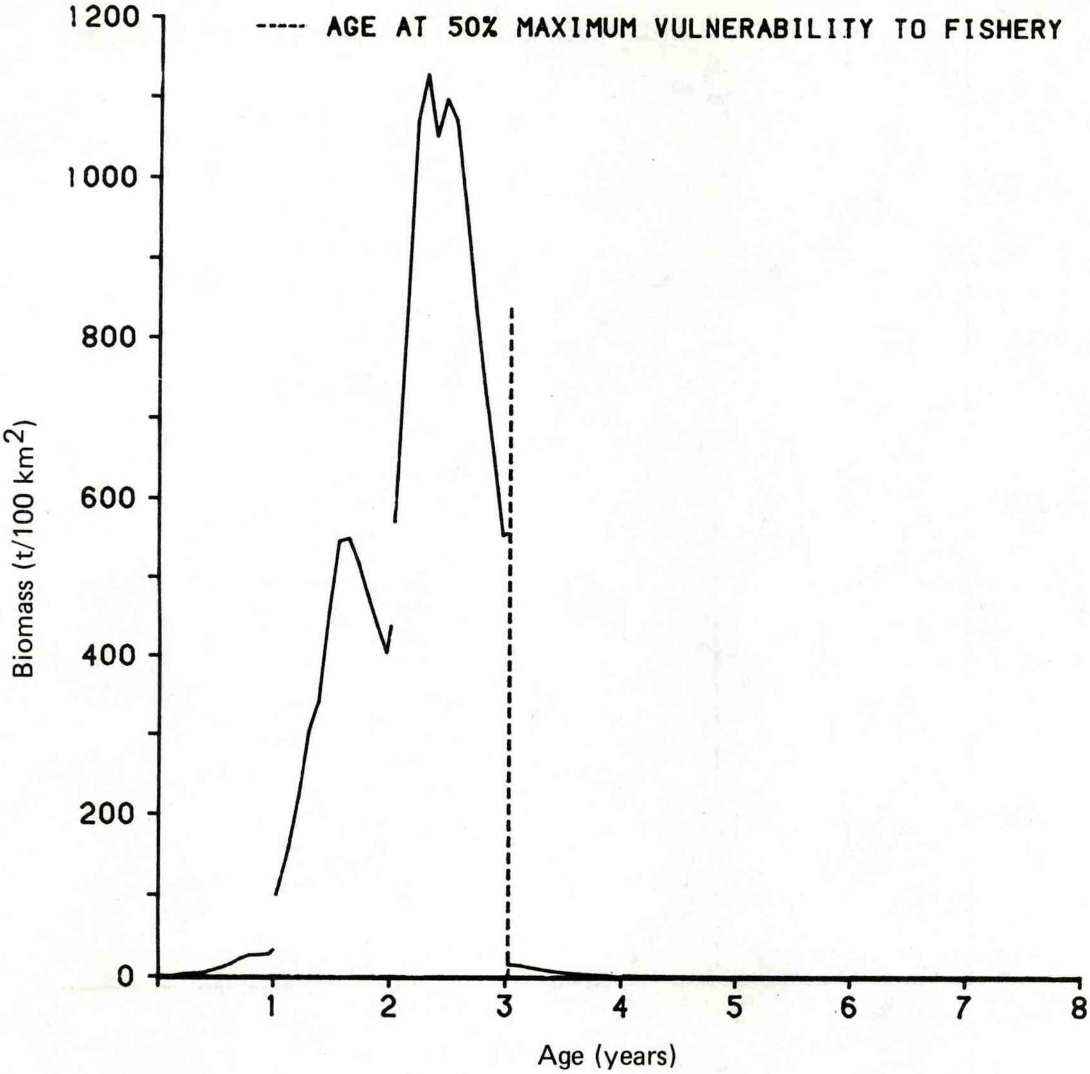

Figure 39.--Walleye pollock biomass-at-age (simulated year 255-256). The annual catch at the end of the year (on 13 May) was 588 t/100 km^2.

the changes in these biomasses during approximate 1-yr time periods which began on 22 May, soon after pollock eggs hatched, and ended on 13 May the following year, immediately before the next hatch. Biomass was a continuous function of time in POL (except for biomass loss at the instant eggs were spawned each 23 April). However, biomass was not a continuous function of age. Consequently the graphs in Figures 33-39 show discontinuities at age-class boundaries, although these graphs would have appeared continuous if stationary biomass distributions had occurred.

The age-classes which were older than the estimated age at 50% maximum vulnerability to the fishery generally were the source of the largest portion of the catch. This was a consequence of the shape of the fishery vulnerability curve (e.g., Figure 20).

When catches were low, strong year-classes of 0- and 1-yr-old pollock remained which were not yet recruited to the fishery (Figure 33). These year-classes grew (Figure 34) and eventually became recruited to the fishery, with resulting increased catches (Figure 35). Some starvation mortality occurred during time periods of increasing catches. During March-May of year 251 and April-May of year 256, 4-yr-old pollock underwent starvation mortality which began before spawning. During April-May of year 255, 3-yr-old pollock underwent starvation mortality which began immediately after spawning. In each year this apparently occurred because of competition for food with an abundant younger age-class (Figures 34, 38, and 39).

The large biomasses of recruited pollock heavily cannibalized younger pollock, which reduced recruitment and caused an eventual decline in catches (Figures 36-37). Surprisingly, starvation mortality did not contribute to the initial decline in catches in this particular cycle. No pollock starvation mortality occurred from 13 May, year 251, until after 1 May, year 253. However, starvation mortality did appear to contribute to the eventual upturn in catches. During May-June of year 253, pollock about age-3 and older underwent starvation mortality after spawning, which reduced the biomass of cannibalistic pollock. The biomass of heavily cannibalistic older pollock was also reduced by intense fishing mortality, as well as decreased recruitment due to previous cannibalism. This permitted the development of strong year-classes of young pollock (Figure 37), which eventually became recruited to the fishery, reversed the decline in catches, and started a new cycle (Figures 38-39).

Fluctuations (apparently caused by the same processes) persisted throughout this 256-yr simulation, and became almost perfectly harmonic with a fundamental period of 14 yr; the third, fifth, and sixth harmonics (with periods of 4.67, 2.80, and 2.33 yr) accounted for 98% of the variation in annual catches during the last 168 yr of the simulation.

The cycles persisted even though during years 251-256 the individual pollock in a cohort tended to grow more slowly when the cohort was relatively strong in numbers and more quickly when the cohort was relatively weak in numbers. This density-dependent growth occurred because the pollock were limited by a finite food production rate. Pollock growth was limited by a finite food supply throughout the entire simulation, which should have caused growth to be density dependent throughout and to dampen the cycles. Apparently, size-specific interactions between cannibalism and recruitment to the fishery were stronger than the effect of density-dependent growth.

4.3.4. Comparisons of Catches with and without Cannibalism

Simulations without cannibalism (P_5=0) were not thought to realistically model the eastern Bering Sea pollock population. They were performed primarily out of a theoretical interest in illustration and comparison of possible qualitative dynamics of populations with and without cannibalism.

From these simulations, the following general qualitative results are evident. In comparison to the population with cannibalism (P_5=1), the population without cannibalism (P_5=0)

1) generally consisted of pollock shorter in length (Figures 28 and 31);
2) on the average produced smaller annual fishery catches (Figures 26 and 29);
3) exhibited a wider range of variation in population size as measured by variation in annual fishery catches (Figures 27 and 30); and
4) exhibited more complex variation in annual fishery catches, as shown by relative numbers of large periodogram ordinates (Tables 44 and 45, compare with Figure 23).

In these simulations, the population with cannibalism exhibited less variation at small values of F (Figure 27). This was apparently because fewer of the large, more cannibalistic pollock were removed by fishing, so that cannibalism exerted a stronger control of population fluctuations. Additionally, less variation was exhibited for small values of length at 50% maximum vulnerability to the fishery (P_{84}). This was apparently because more of the small pollock were removed by fishing, dampening potential fluctuations early in the age structure.

In contrast, fluctuations in the population without cannibalism markedly decreased only for some combinations of large values of F and small values of P_{84} (Figure 30). This was probably because only under these circumstances were removals by the fishery large enough to dampen fluctuations. The major cause of the wide fluctuations exhibited with no cannibalism seemed to be a tendency for simulated pollock population levels to increase until severe starvation mortality caused drastic reductions by one or more orders of magnitude (e.g., Figure 23).

4.4. Pollock Growth without Food Limitations

In the previously described simulations, it became evident that the pollock population levels and individual lengths and weights were limited by the food supply. Some consequences of this were the starvation mortality (condition-dependent mortality) which occurred in many of the simulations, the observed maximum length and weight limitations, and the frequent inverse relationship observed between the population numbers of a pollock cohort and the weight of individuals in that cohort. This food limitation undoubtedly also influenced the pollock fishery catch isopleths. As additional verification that the simulated growth of pollock was limited by food supply, pollock growth without a food limitation was simulated. This was done as follows.

The population size of each cohort (variable N_i) was forced to continuously equal 10 pollock. This was accomplished by altering the FORTRAN implementation of the model slightly, so that E (the number of pollock eggs surviving to hatch) was always set equal to 10, and each N_i' (the derivative with respect to time of the population numbers in pollock cohort i) was always set equal to 0. The pollock were forced to grow as if the food supply was unlimited by using the equation

$$W_i' = \text{MIN}[P_3, P_{117} \times W^{P_{118}}] \times [\text{UMAXFD}_i - P_1 \times W_i^{P_2}], \tag{9}$$

where W_i' is the derivative of individual wet weight for cohort i; and P_1, P_2, P_3, P_{117}, and P_{118} are parameters. Also,

$$\text{UMAXFD}_i = P_7 \times \text{EATER}_i \times L_i^{P_{119}} \tag{10}$$

where P_7 and P_{119} are parameters, EATER_i is a relative maximum feeding rate (which could vary with the breeding condition or the age of the pollock), and L_i is the fork length of pollock in cohort i. The reference set of parameters and initial conditions was used; the resulting lengths and weights (on simulated date 13 May, year 23, after stationary conditions had occurred) are shown in Table 46. For comparison, simulated stationary pollock lengths and weights are also shown (for simulated date 13 May, year 49) which were calculated with the unmodified FORTRAN implementation of POL using the reference set of parameters and initial conditions. The differences in growth rates are large, especially for pollock more than 1 yr in age, indicating that pollock were indeed limited by food supply during much of the simulated year using the reference set of parameters. This is not surprising considering the wide seasonal fluctuations in simulated zooplankton biomass caused by seasonal variation in the simulated primary production rate. The maximum length observed for pollock is listed by Hart (1973) as 91 cm, which is much less

Table 46.--Comparison of the simulated growth of walleye pollock under conditions of normal and unlimited food supply. Normal growth was calculated using an unmodified implementation of the model. Data values listed are for 13 May after stationary conditions occurred; the reference set of parameters and initial conditions was used.

Food Supply	Age (year)	Weight (g)	Annual growth in weight (g)	Length (cm)	Annual growth in length (cm)
Normal	1	19.6	19.6	13.3	12.9
	2	110	90.3	25.4	12.1
	3	262	152	35.8	10.4
	4	420	158	42.5	6.66
	5	558	138	46.4	3.90
	6	682	124	49.0	2.60
	7	790	108	50.9	1.95
	8	884	93.9	52.4	1.51
	9	965	81.0	53.6	1.21
	10	1,030	66.7	54.6	0.971
	11	1,090	55.1	55.4	0.755
	12	1,130	44.7	56.0	0.593
	13	1,170	36.2	56.4	0.468
	14	1,200	29.0	56.8	0.369
	15	1,220	23.2	57.1	0.291
	16	1,240	18.6	57.3	0.232
Unlimited	1	59.2	59.2	18.8	18.3
	2	848	788	48.1	29.3
	3	3,920	3,070	74.0	25.9
	4	10,100	6,190	96.1	22.1
	5	19,800	9,710	116	19.6
	6	33,200	13,300	133	17.5
	7	50,000	16,800	149	15.9
	8	70,000	20,100	164	14.5
	9	93,000	23,000	177	13.2
	10	118,000	25,500	189	12.1
	11	146,000	27,600	200	11.2
	12	175,000	29,300	210	10.3
	13	206,000	30,600	220	9.49
	14	238,000	31,600	229	8.78
	15	270,000	32,300	237	8.13
	16	303,000	32,600	244	7.54
	17	335,000	32,700	251	7.00
	18	368,000	32,600	258	6.51
	19	400,000	32,300	264	6.05
	20	432,000	31,800	269	5.63

than the maximum of 269 cm FL achieved by the simulated pollock with no food limitation. It may be that all pollock so far observed in nature have been food limited; it would be interesting to observe the growth rates achieved by a healthy pollock in a large aquarium with unlimited food over a time span of 15 or more yr. Hart (1973:229), cited Lamb (pers. commun.), who found that under aquarium conditions lengths of pollock may exceed 30 cm in the second summer. This seems comparable to the fork length of 27 cm achieved by simulated pollock 1.3-yr-old on 1 September (having lived through two simulated summers) which had never been limited by food supply. Nonetheless, it is not claimed that pollock much larger than 90 cm would occur in nature if growth was unlimited by food supply or energy losses to parasites. Processes not modeled in POL would probably intervene to limit growth.

The food supply limitation on simulated pollock using the reference set of parameters did not begin to take effect until the autumn and winter season of the first year of life. For example, simulated 0.3-yr-old pollock measured 5.64 cm FL and weighed 0.784 g on 1 September after the occurrence of stationary conditions, when the unmodified implementation of POL was used with the reference set of parameters and initial conditions. This was almost exactly the same as the 5.65 cm and 0.785 g achieved by pollock of the same age in the simulation without food limitation.

5. DISCUSSION

5.1. Overview of Significant Results

5.1.1. Model Validity

The various validation exercises showed that POL explained much of the observed variation in eastern Bering Sea pollock catches, numbers, weights, and lengths, although statistically significant differences also occurred (Table 7).

This indicates that POL or similar calibrated models are valid for many purposes. For example, POL should be usable as one indication of the status of pollock stocks and as a predictor of future catches. It also indicates that although POL is usable for such purposes, further improvements may be desirable. This is discussed in suggestions for future studies, Section 5.3.

5.1.2. Sensitivity to Parameter Values

Model results are sensitive to changes in the parameter values. "Sensitive" means that qualitative or quantitative model behavior can be significantly changed with parameter values which otherwise appear realistic according to present knowledge. Previous sections showed the sensitivity of model results to parameter values for the effective area of the pollock population exploited by the fishery, pollock catchability (q), pollock prey switching (P_{76}), maximum pollock feeding rate (P_7, P_{17}, P_{114};[3/] P_{119}), relative vulnerability of pollock to cannibalism (P_5), length of pollock at

3/ Semicolons are used in parenthetical lists in this section to separate groups of conceptually related parameters from less similar groups. See also parameter definitions given in Knechtel and Bledsoe (1981:appendix A).

50% maximum vulnerability to the fishery (P_{84}), and maximum fishing mortality rate (F). In addition, during at least part of the model calibration process, it appeared that some aspects of model behavior were sensitive to parameter values for the following: primary production by phytoplankton (P_{11}, P_{27}); respiration, molting, and otherwise unaccounted for mortality rates of phytoplankton, copepods, and euphausiids (P_{39}, P_{47}, P_{57}); copepod and euphausiid feeding rates (P_{43}; P_{51}; P_{49}, P_{50}, P_{69}); pollock condition-dependent or starvation mortality (P_{71}, P_{72}, P_{73}); pollock weight-dependent or "predation" mortality (P_{97}, P_{98}); pollock natural mortality not otherwise accounted for (array M); pollock feeding as a function of food density (P_8, P_{18}; P_9, P_{19}; P_{101}, P_{102}); food size selectivity of pollock (P_{16}, P_{79}; P_{58}, P_{78}); pollock growth in length (P_{89}, P_{94}, P_{95}, P_{96}; P_{90}, P_{106}; P_{104}, P_{105}); pollock weight or energy loss as a result of spawning (P_{10}); and initial weight of larval pollock (P_{13}). It is probable that in many cases the model would also be sensitive to changes in the present reference set of values for these parameters; this may be studied in the future. It is also almost certain that some aspects of model behavior are sensitive to the values of parameters not in the above lists; a list of these parameters is given in the section on suggestions for future studies.

5.1.3. Equilibrium, Periodic, and Pseudorandom Behavior

For various parameter values the model displayed either equilibrium behavior (i.e., stationary behavior, which was defined to be periodic behavior with an annual cycle, but without longer term periodicities), persistent periodic cycles with periods longer than 1 yr, or pseudorandom (chaotic) behavior. Cannibalism seemed to be stabilizing in the sense that it led to equilibrium behavior or periodic cycles. These results support the idea that equilibrium, periodic, and pseudorandom behavior can occur in actual population dynamics as a result of age structure or cannibalism, distinct from exogenous fluctuations in food supply or environment.

5.1.4. Tendency toward Equilibrium

Using the reference set of parameters and initial conditions, the annual simulated catches of walleye pollock stayed within about ±10% of the final stationary value of about 113 t/100 km^2 beginning in simulated year 10 (see Figure 1); the simulation run was stopped in simulated year 49 because stationary conditions occurred. This indicated that the actual pollock population may tend toward equilibrium in the existing fishery. However, a model calibration criterion was that final nontransient catches be approximately 100 t/100 km^2. Although fluctuating catches were not ruled out, this may have biased the calibration process toward such an equilibrium level. Whether the model reached equilibrium or not was dependent on parameter values to which the model was sensitive (e.g., Table 28, Figure 23). It is possible that a reasonable set of parameters and initial conditions modeling the present fishery could be found which would result in significant persistent fluctuations in simulated annual pollock catches. In addition, factors not modeled in detail could also cause fluctuations; for example, physical environmental fluctuations and competition with or predation by other species could cause significant persistent fluctuations in the pollock population.

Just as the behavior of POL was sensitive to certain parameter changes, the qualitative behavior of the population dynamics of pollock in nature might change as a result of changes in ecological and biological conditions. For example, it has been hypothesized that relatively small, long-term changes in average temperature might cause greater geographic separation between large and small pollock (K. Bailey, Northwest and Alaska Fisheries Center, 2725 Montlake Blvd. E., Seattle, WA 98112; pers. commun., 1982). This could decrease the relative vulnerability of small pollock to cannibalism and generate persistent fluctuations in annual catch rates (Figure 23). Such a departure from an apparent or approximate equilibrium might take two or more years to become noticeable, due to the inertial effect of existing age-classes and the annual nature of the pollock reproductive cycle.

5.1.5. Pollock Food Supply Limitation

For the reference set of parameters and initial conditions, all cohorts of pollock grew to less than the maximum possible length and body weight for that cohort. This was caused by lack of food during at least part of the simulated year. In addition, two cohorts (about age 4 or 5 yr) suffered condition-dependent mortality (starvation mortality) shortly after spawning. On the basis of simulations with POL, it seems reasonable to expect pollock in nature to be limited by food supply, with the exception that juvenile pollock are not expected to be limited by food supply until their first fall or winter.

5.1.6. Recovery from Overfishing

As indicated by total ova production (Table 27), the simulated pollock population was capable of recovery from severe overfishing to a condition close to its unfished state in less than about 16 yr. Extinction was an attractor at only extremely low population levels--if even 1.1 pollock/100 km^2 survived to spawn, recovery occurred when overfishing was stopped. No multiple stable points (equilibria) or different stable (nontransient) cycles were found to occur as a result of different initial conditions for the differential equations. The only exception was the equilibrium point of total extinction of the pollock population when no "immigration" was allowed (P_{74}=0), because in that case the pollock remained extinct. However, it may be possible that nonzero multiple equilibria or different stable cycles could be found with further searching. The fishery vulnerability curve used was a monotone increasing logistic function of pollock length (e.g., Figure 20); if a curve with a maximum had instead been used (representing increased fishery targeting on an intermediate size-class of pollock, but decreased targeting on smaller and larger size-classes of pollock) it is also possible that multiple equilibria or different stable cycles as a result of different initial conditions could have been found. Such a curve might occur in a fishery for pollock chiefly used for surimi (Wespestad and Terry in press).

Additionally, it is possible that mechanisms not modeled could cause multiple equilibria or different stable cycles. For example, it might be possible for competitors of pollock to "take over" its ecological niche after overfishing and prevent the population from returning to previous levels, even without fishing.

5.1.7. Possibility of Large Sustainable Increases in Pollock Catches

Some combinations of decreased length of pollock at 50% maximum vulnerability to the fishery (P_{84}) and increased maximum fishing mortality rate (F) led to more than five- or six-fold increases in the simulated long-term average fishery yield, compared to the present fishery. This represents emergent model behavior, i.e., behavior which was not an inevitable result of model assumptions or the calibration process. It also represents a prediction or extrapolation about some of the possible consequences of a greatly increased pollock fishery, based on historical data about the eastern Bering Sea ecosystem and data from other ecosystems and fisheries. The prediction of large increases in fishery yields should be regarded as tentative, probably requiring further verification using data from the Bering Sea pollock population, as well as further examination of effects not modeled in POL (see the section on suggestions for further studies). It is interesting to note that commonly used, more simplistic approaches to stock analysis are, in general, mathematically incapable of predicting such large increases in fishery yield. Reasons for this are discussed in Section 5.2.5, which compares the results of this study with the results of Chang (1974).

Any proposal to increase pollock fishery yield, in addition to considering the need to verify the results of POL, should also make allowances for the following facts. Some combinations of P_{84} and F greatly increased the variability of the simulated annual pollock catches and might decrease the body size of pollock in the catch--these effects could impose some limitations on the desirability of increased catches. The actual value of F is uncertain; also, underreporting may cause it to be underestimated. The actual shape of the pollock vulnerability curve to the fishery is uncertain; and changes in vessels, gears, and technologies will probably cause future changes. Predicted catches of pollock were sensitive to changes in other model parameters besides F and P_{84} (e.g., Table 28, Figure 23). Increased pollock catches also may have adverse consequences for other parts of the eastern

Bering Sea ecosystem; examples regarding zooplankton are discussed in the next section.

5.1.8. Possibility of Reduced Plankton Biomasses Resulting from an Increased Pollock Fishery

As shown in Tables 47-52, increases in F (maximum fishing mortality rate) and intermediate values of P_{84} (length at 50% maximum vulnerability to the fishery) lowered minimum values and increased fluctuations of the biomasses of simulated phytoplankton, copepods, and euphausiids measured on 13 May; values throughout the year were probably similarly affected. The fluctuations in zooplankton biomass were probably initially caused by a large biomass of small pollock which consumed large amounts of zooplankton; future studies may explore this in more detail.

In addition, it was found that without pollock prey switching (i.e., with P_{76}=0), the model euphausiids became extinct with an intense fishery (P_{84}=40 cm, and F=2.4 or 3.0 year^{-1}).

Since plankton are important prey items in the eastern Bering Sea ecosystem, an increased fishery for pollock might indirectly have an adverse effect on species preying on plankton. This points out the need for multispecies models to predict the effects of an intense fishery for pollock.

Plankton biomasses were not modeled as driving (forcing) functions in POL, but instead were truly dynamic model components. The large fluctuations in plankton biomasses caused by an indirect interaction with the pollock fishery, together with the result that pollock are food limited, confirm that zooplankton and phytoplankton biomasses (standing stocks) should not be

Table 47.--Minimum standing stock of phytoplankton (g C/m^2) on 13 May, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
0.3	11.1	11.1	11.0	11.0	11.0	11.0	11.0	10.9
0.6	11.2	11.1	11.1	11.0	10.9	10.8	10.7	10.9
0.9	11.3	11.3	11.2	10.9	10.7	10.6	10.6	10.7
1.2	11.5	11.4	11.2	10.9	10.6	10.5	10.5	10.6
1.5	11.6	11.5	11.3	10.7	10.5	10.3	10.3	10.5
1.8	11.7	11.6	11.4	10.6	10.3	10.0	10.1	10.4
2.1	11.8	11.7	11.4	10.4	9.8	9.3	9.6	10.2
2.4	11.7	11.7	11.4	10.0	9.4	8.7	9.0	10.0
2.7	11.5	11.7	11.1	9.9	9.3	8.4	8.2	9.6
3.0	11.4	11.7	11.0	10.3	9.2	8.3	8.1	9.3

a/ The area modeled was assumed equal to 100 km^2. Data values were calculated from the last 201 yr of a 256-yr simulation.

Table 48.--Ratio of the minimum standing stock of phytoplankton to the maximum, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).a/

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.0	1	1	1	1	1	1	1	1
0.3	1	1	0.998	1	1	1	1	1
0.6	1	1	1	1	0.978	0.964	0.961	1
0.9	1	1	1	0.976	0.947	0.930	0.932	0.942
1.2	1	1	1	0.955	0.928	0.908	0.912	0.925
1.5	1	1	1	0.923	0.901	0.877	0.886	0.911
1.8	1	1	1	0.893	0.872	0.839	0.854	0.891
2.1	1	1	1	0.860	0.822	0.763	0.796	0.872
2.4	1	1	0.983	0.819	0.775	0.711	0.732	0.852
2.7	1	1	0.938	0.802	0.752	0.681	0.667	0.811
3.0	1	1	0.907	0.841	0.745	0.667	0.652	0.780

a/ Data values were measured on 13 May during the last 201 yr of a 256-yr simulation.

Table 49.--Minimum standing stock of copepods (g wet weight/m^2) on 13 May, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).[a/]

F	P_{84} (cm)							
($year^{-1}$)	10	15	20	25	30	35	40	45
0.0	53	53	53	53	53	53	53	53
0.3	50	51	51	52	53	53	53	53
0.6	47	49	50	52	50	48	48	54
0.9	44	46	48	47	45	42	42	45
1.2	40	43	46	43	41	38	39	41
1.5	37	40	45	38	36	34	36	39
1.8	35	38	43	32	33	29	32	37
2.1	33	37	42	27	29	26	28	35
2.4	35	35	38	23	26	23	23	33
2.7	39	35	31	21	21	21	23	31
3.0	43	36	26	22	21	18	20	30

a/ The area modeled was assumed equal to 100 km^2. Data values were calculated from the last 201 yr of a 256-yr simulation.

Table 50.--Ratio of the minimum standing stock of copepods to the maximum, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).[a/]

F (year^{-1})	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.0	1	1	1	1	1	1	1	1
0.3	1	1	0.992	1	1	1	1	1
0.6	1	1	1	1	0.895	0.833	0.821	1
0.9	1	1	1	0.878	0.756	0.684	0.693	0.739
1.2	1	1	1	0.781	0.675	0.595	0.615	0.666
1.5	1	1	1	0.637	0.568	0.492	0.530	0.612
1.8	1	1	1	0.517	0.474	0.388	0.439	0.547
2.1	1	1	1	0.405	0.362	0.269	0.322	0.491
2.4	1	1	0.890	0.306	0.285	0.211	0.225	0.442
2.7	1	1	0.638	0.264	0.221	0.176	0.182	0.366
3.0	1	1	0.493	0.323	0.212	0.152	0.155	0.317

a/ Data values were measured on 13 May during the last 201 yr of a 256-yr simulation.

Table 51.--Minimum standing stock of euphausiids (mg wet weight/m^2) on 13 May, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).[a/]

F	P_{84} (cm)							
(year^{-1})	10	15	20	25	30	35	40	45
0.0	53	53	53	53	53	53	53	53
0.3	38	38	37	39	41	43	45	47
0.6	29	28	28	31	28	26	27	44
0.9	24	22	22	21	19	18	19	22
1.2	20	18	18	15	14	13	14	17
1.5	19	16	15	10	10	9	11	14
1.8	21	15	14	6	7	7	8	12
2.1	30	16	14	3	3	3	6	11
2.4	53	20	12	2	2	2	3	9
2.7	112	29	8	1	2	2	2	8
3.0	184	50	4	1	1	1	2	5

a/ The area modeled was assumed equal to 100 km^2. Data values were calculated from the last 201 yr of a 256-yr simulation.

Table 52.--Ratio of the minimum standing stock of euphausiids to the maximum, as a function of F (maximum fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery), when accompanied by walleye pollock cannibalism (P_5 = 1).[a/]

F ($year^{-1}$)	P_{84} (cm)							
	10	15	20	25	30	35	40	45
0.0	1	1	1	1	1	1	1	1
0.3	1	1	0.963	1	1	1	1	1
0.6	1	1	1	1	0.681	0.531	0.494	1
0.9	1	1	1	0.663	0.411	0.297	0.290	0.324
1.2	1	1	1	0.463	0.298	0.201	0.196	0.235
1.5	1	1	1	0.255	0.184	0.140	0.139	0.182
1.8	1	1	1	0.134	0.112	0.100	0.106	0.146
2.1	1	1	1	0.054	0.047	0.040	0.064	0.135
2.4	1	1	0.730	0.028	0.034	0.019	0.029	0.108
2.7	1	1	0.266	0.018	0.016	0.011	0.012	0.082
3.0	1	1	0.084	0.021	0.010	0.008	0.009	0.051

a/ Data values were measured on 13 May during the last 201 yr of a 256-yr simulation.

modeled as driving functions when attempting to simulate the effects of large changes in the fishery for pollock in the eastern Bering Sea.

It should be noted that all simulated pollock eggs produced in a breeding season hatched at the same time in POL, when in reality pollock eggs and larvae appear over a period greater than 2 mo (for an example in the case of the northeastern Sea of Japan, see Zver'kova 1977:fig. 6). This spread may lessen somewhat the actual impact small pollock have on zooplankton populations. Nonetheless, the appearance of pollock larvae does occur with a distinct peak (e.g., Waldron and Vinter 1978:table 8), which may indicate that the simplification used in POL of having all pollock larvae hatch at the same time did not cause effects qualitatively different from reality.

5.2. Comparisons to Other Studies

5.2.1. Polis (1981)

Polis (1981) reviewed a large number of papers discussing intraspecific predation (cannibalism) in about 1,300 species. There were many similarities between his findings and the results reported here.

For example, Polis found that in general larger (older) animals are more voracious cannibals than smaller (younger) animals, with the smaller specimens being more often eaten than the larger. This was also the case with pollock simulated using POL. Using the reference set of parameters and initial conditions, 0, 1, and very small numbers of 2-yr-old pollock (about 2.9-26 cm FL) were cannibalized after the occurrence of stationary conditions, with the maximum instantaneous mortality rates from cannibalism (MT_1>36 year^{-1}) occurring among pollock about 6 cm FL (<1-yr-old) in early September when alternative food sources (copepods and euphausiids) were declining. Pollock larger than about 17.6 cm FL (>1 yr old) obtained part of their diet by cannibalism, with the percentage of the diet consisting of other pollock increasing (and the percentage consisting of zooplankton decreasing) with increasing length. At times, >60% of the diet of the larger-size classes consisted of other pollock.

Polis remarked that cannibalism may occur as a by-product of the normal feeding behavior of some species; cannibalism was also modeled in this manner in POL. For example, the occurrence of cannibalism in POL did not depend on the "level of starvation" of potential cannibals.

Polis noted that cannibalism could be a major mortality factor. This was the case in POL (Table 53). Using the reference set of parameters and initial conditions, after stationary conditions occurred pollock less than 2-yr old (cohorts 1-2) were especially heavily cannibalized.

Polis stated that cannibalism could operate as a density-dependent regulator of population size which could either dampen or cause population fluctuations. As discussed previously, this was also found to be the case in POL. Two of the potential regulatory feedback loops Polis reported between cannibalism and ambient food levels also appeared to operate in POL: first, as conspecifics are eaten, the population of intraspecific competitors declines and the per capita food level increases; secondly (if food is limited, as was the case in POL with the reference set of parameters and initial conditions), as density increases, both per capita food and growth decrease, which results in smaller conspecifics that are more frequently eaten.

Table 53.--Sources of mortality of simulated pollock cohorts 1-3, after the occurrence of stationary conditions while using the reference set of parameters and initial conditions.

Pollock cohort i	Total mortality ($year^{-1}$)	Percentage of total mortality				
		Cannibalism mortality (MT_i)	Weight-dependent mortality ($UPRED_i$)	Starvation mortality (SM_i)	Fishing mortality ($UFISH_i$)	Other mortality (M_i)
1	8.8	69% a/	29%	0	b/	2%
2	0.50	60%	b/	0	b/	40%
3	0.22	b/	b/	0	11%	89%

a/ Calculated by averaging the value of MT_1 for 1 yr using points 0.02 yr apart.
b/ Less than 0.5%

Polis commented that cannibalism decreases the ecological efficiency of secondary production. This appeared to occur in POL. For instance, large increases in simulated average annual catches of pollock (Figure 26) occurred for combinations of F (fishing mortality rate) and P_{84} (length at 50% maximum vulnerability to the fishery) which selectively removed the larger, slower growing, more cannibalistic pollock while still allowing enough pollock (of sufficient size to be fecund) to escape to renew the stocks, so that ecological efficiency was increased. However, other factors (such as increased growth and fecundity of simulated pollock in cohorts with reduced population numbers) probably also influenced the shape of the catch isopleths in Figure 26.

Polis remarked that cannibalism may also influence population energetics when young animals function as de facto "grazers," thus effectively increasing the carrying capacity of the reproductive population. He listed references to several species of fish as examples. An initial examination seemed to indicate that this was the case in POL; for instance, simulated average annual catches of pollock were higher with cannibalism than without for $P_{84} \geq 25$ cm FL (Tables 30-31), which indicated higher biomasses of larger, more sexually mature pollock existed when there was cannibalism. However, a more detailed investigation uncovered additional complexities which are discussed below.

Polis listed three conditions necessary to cause cannibalism on young grazers to increase the carrying capacity of reproductive animals:

1) "Immature animals feed on resources inaccessible to or unutilized by the adults." All size-classes of pollock in POL fed on zooplankton.

However, using the reference set of parameters and initial conditions, after the occurrence of stationary conditions the percentage of zooplankton in the diet of pollock $\geq$1 yr old decreased with increasing length. Because of the shape of the pollock food size selection function, the availability of zooplankton as food was forced to decrease with increasing length for pollock >15.6 cm FL.

2) "Adults feed on immature animals and thus indirectly incorporate these previously unavailable resources." Using the reference set of parameters and initial conditions, after the occurrence of stationary conditions the highest cannibalism mortality rates occurred among pollock <1 year old in POL. Spawners consisted only of pollock almost 2 yr old or older.

3) "Food is limiting to the adult population so that an increase in food intake can be converted into a higher carrying capacity." As discussed previously, all adult size-classes of pollock were limited by food supply in POL using the reference set of parameters and initial conditions.

Thus Polis' three conditions essentially appeared to be met for the reference set after the occurrence of stationary conditions. Consequently if cannibalism were increasing the carrying capacity of mature pollock in POL, one might expect a small decrease in the relative vulnerability to cannibalism (P_5) to cause a decrease in the total number of ova produced in a given breeding season, because the number of ova was proportional to the biomass of mature female pollock. This was the case in POL for some combinations of F and P_{84}--but not for the reference set (Table 54). One hypothesis as to why this occurred is that lower vulnerability to cannibalism allowed more of the small pollock to grow to larger weights before being cannibalized, so that the

Table 54.--Number of walleye pollock eggs produced annually as a function of relative vulnerability to cannibalism and fishery parameters.

P_5, relative vulnerability to cannibalism	P_{84}, length at 50% maximum vulnerability to fishery (cm)	F, maximum fishing mortality ($year^{-1}$)	ETT,a/ total ova laid ($number/m^2$)
1.0 b/	40	0.3	480
0.95	40	0.3	510
0 c/	40	0.3	120
1.0	20	2.1	34
0.95	20	2.1	33

a/ If stationary conditions occurred, the last value simulated was used. Otherwise, the average of the final 201 yr of a 256-yr simulation was used.

b/ The parameters in this row belonged to the reference set of parameters.

c/ The simulation which used the parameters in this row also used P_{74} = 10 (immigration of cohort-1 pollock was allowed under some circumstances).

total biomass of small pollock "harvested" by the larger pollock was increased. In other words, increases in size at the time of consumption may have compensated for decreased vulnerability to cannibalism. This is analogous to the way yield per recruit in some cases can be increased in a Beverton and Holt (1957) yield per recruit model by decreasing the fishing mortality rate, so that more fish grow to a larger weight before being caught. This result is not a counterexample to Polis' three conditions, but rather an indication that the cannibalization rates were not optimal in the sense of maximizing the biomass of mature female pollock after the occurrence of stationary conditions. With P_5=0, the mean value of ETT decreased. Such a decrease was expected since Polis' three conditions were essentially fulfilled for the reference set of parameters.

In another example from Table 54, if P_{84}=20 cm and F=2.1 year^{-1}, then a small decrease in P_5 resulted in a slight but significant decrease in ETT. This decrease is what one would expect if Polis' conditions were fulfilled, and cannibalism was at a more optimal level and timing in terms of increasing the carrying capacity of mature female pollock. The growth rate of the youngest cohorts for this combination of F and P_{84} was slower than for the reference set (see Table 55), so that increases in size at the time of consumption apparently did not compensate for decreased vulnerability to cannibalism. It may be hypothesized that this combination of F and P_{84} qualitatively simulated the effect of an increased biomass of marine mammals preying on pollock. Such an increased biomass of marine mammals might have existed in the Bering Sea in the past before their heavy exploitation by man beginning in the 18th century.

Table 55.--Comparison of simulated cannibalistic walleye pollock populations under present and intense fishing conditions. In both cases, relative vulnerability to cannibalism, P_5, equaled 1. Values shown were immediately before cohort update on 13 May, after stationary conditions had occurred.

Present fishery a/

Age (year)	Number N_i (No./10^6 km^2)	Biomass B_i ($t/10^6$ km^2)	Length L_i (cm)	Weight W_i (g)
1	8.8×10^9	1.7×10^5	13.3	19.6
2	5.3×10^9	5.9×10^5	25.4	110
3	4.3×10^9	1.1×10^6	35.8	263
4	2.7×10^9	1.2×10^6	42.5	421
5	1.2×10^9	6.9×10^5	46.4	559
6	5.6×10^8	3.9×10^5	49.0	684
7	2.8×10^8	2.2×10^5	50.9	792
8	1.4×10^8	1.2×10^5	52.5	886
9	6.9×10^7	6.7×10^4	53.7	968
10	3.4×10^7	3.5×10^4	54.6	1,030
11	1.7×10^7	1.8×10^4	55.4	1,090
12	6.3×10^6	7.1×10^3	56.0	1,130
13	1.7×10^6	2.0×10^3	56.5	1,170
14	3.5×10^5	4.2×10^2	56.8	1,200
15	7.0×10^4	86	57.1	1,220
16	1.4×10^4	17	57.3	1,240
Total	2.3×10^{10}	4.6×10^6		

Intense fishery b/

Age (year)	Number N_i (No./10^6 km^2)	Biomass B_i ($t/10^6$ km^2)	Length L_i (cm)	Weight W_i (g)
1	5.1×10^{10}	9.0×10^5	13.0	17.6
2	1.1×10^{10}	1.1×10^6	24.8	98.9
3	1.1×10^9	2.8×10^5	35.5	257
4	1.1×10^8	4.8×10^4	42.4	435
5	1.0×10^7	6.6×10^3	47.2	659
6	8.2×10^5	8.1×10^2	52.3	991
7	6.8×10^4	1.2×10^2	60.1	1,710
Total	6.3×10^{10}	2.3×10^6		

a/ Annual fishery catch was 1.1×10^6 $t/10^6$ km^2; total number of pollock eggs surviving to hatch each spring was 61 eggs/m^2. Simulation parameters used were length at 50% maximum vulnerability to fishery = P_{84} = 40 cm, and maximum fishing mortality rate = F = 0.3 $year^{-1}$.

b/ Annual fishery catch was 5.7×10^6 $t/10^6$ km^2; total number of pollock eggs surviving to hatch each spring was 4.2 eggs/m^2. Simulation parameters used were length at 50% maximum vulnerability to fishery = P_{84} = 20 cm, and maximum fishing mortality rate = F = 2.1 $year^{-1}$.

An interesting unanswered question is, "What is an 'optimum' cannibalism rate for an animal, in the sense of natural selection or optimum foraging?" It is likely to be a complex function of processes determining an optimum, including growth rates, mortality rates from other sources, conversion efficiencies, fecundities, food abundances, and other factors. Furthermore, feeding habits which were optimum in the past or over long periods of time might not be optimum at present (e.g., Allen 1982)--present conditions might represent an anomaly.

Though not discussed by Polis, if cannibalism is not at an optimum level, then some spawning stress mortality soon after spawning might confer selective benefits, because it could act to reduce the amount of subsequent cannibalism. Consequently, it is interesting to note that spawning stress mortality is thought to occur in the present pollock population (Chang 1974:118; Vyshegorodtsev 1978). In POL, some pollock cohorts underwent spawning stress mortality after spawning weight loss in the simulation in which cannibalism was less optimal (P_5=1, F=0.3 year^{-1}, P_{84}=40 cm), which was thought to approximately correspond to the present eastern Bering Sea pollock population and fishery. This resulted from food limitation, i.e., starvation. In contrast, no cohorts underwent starvation mortality at any time after stationary conditions occurred in the simulation in which cannibalism was apparently more optimal (P_5=1, F=2.1 year^{-1}, P_{84}=20 cm).

Polis extensively discussed the possibilities of genetic selection for cannibalism on the individual, kin, and group levels, although he also noted that cannibalism need not necessarily be adaptive and a product of natural selection. From the results of simulations with POL, it appears cannibalistic pollock genotypes could be given selective advantages by a wider variety of possible foods for the individual, cannibalistic regulation of population fluctuations, and increased carrying capacity of mature female pollock when heavily exploited. However, the model POL was not designed to simulate the effects of genetic selection.

5.2.2. May and Oster (1976)

May and Oster (1976) described the population dynamics of a simple hypothetical population determined by certain kinds of deterministic stock-recruitment relationships. They used a version of the Ricker recruitment curve (Ricker 1975:eq. 11.14) as their primary example. This curve may be appropriate to model stock recruitment when cannibalism of young by adults is an important regulatory mechanism (Ricker 1975:281). May and Oster found that a stable equilibrium, a periodic oscillation, or a chaotic (pseudorandom) oscillation could occur in the simulated population, depending on a parameter value used in the stock-recruitment curve. As discussed previously, these three categories of behavior were also observed to occur for different parameter values of POL. This seems to be a good example of how a simple model can qualitatively reproduce some aspects of the behavior of a more complex model.

May and Oster also noted that if extinction was an attractor, and if sufficiently low population levels could result from higher population levels, then extinction would almost surely result, particularly in the case of the chaotic regime. This was also the case in POL. For example, using the reference set of parameters and initial conditions (so that $P_{74}=0$, meaning "immigration" of cohort-1 pollock was not allowed and pollock extinction was possible), but with P_5=0 (no cannibalism allowed), the model behaved chaotically (pseudorandomly). The simulation was stopped in simulated year 94 because the entire pollock population had become extinct. However, due to spatial heterogeneity not included in POL, such extinction may be unlikely in nature. For this reason, a small amount of pollock "immigration" (P_{74}=10) was allowed under some circumstances in many simulations. Other phenomena not modeled in POL (e.g., competition with other species for food supply, habitat, or some other limited resource) might result in pollock extinction in nature.

5.2.3. Gurtin and Levine (1982)

Gurtin and Levine (1982) modeled a theoretical animal population with a structure described by a partial differential equation using derivatives with respect to time and age. They made various assumptions in order to analyze the model. One of these assumptions was that the expected birth rate of an individual of a given age was described by a function which decreased to a limit of 0 as age increased. This type of age-dependent fecundity seems qualitatively different from the fecundity of fish such as pollock. This is because the expected fecundity (number of ova) of pollock is approximately a linearly increasing function of weight (Shew 1978), and the expected weight of pollock increases with age (e.g., Figure 13). Gurtin and Levine also assumed all deaths by cannibalism occurred at the instant of "birth."

Gurtin and Levine used three quantities (which were integrated with respect to age) to describe the state of the modeled population at a given time: total population (P), total birth rate (B), and a quantity (A) related to the age-specific birth rate of the population. Under the assumptions made by Gurtin and Levine, these three quantities were determined by a system of three simultaneous first-order, nonlinear, ordinary differential equations. It was not necessary to solve these equations to determine some qualitative aspects of the dynamics of the population modeled. For example, if the expected number of young born to an individual in its lifetime to survive cannibalism was >1 when B and P were close to 0, then extinction could not occur. This was qualitatively similar to POL, where extinction did not occur if even 1.1 pollock/100 km^2 survived to spawn, despite the numerous differences between the two models.

Because of the complexity of the general behavior of their model, Gurtin and Levine analyzed three special cases using different sets of simplifying assumptions.

Under one set of assumptions (including the assumption that the fraction of newborns surviving cannibalism (g) was a monotone increasing function of the birth rate per unit population), all trajectories tended to equilibrium. For some parameter sets in POL (e.g., Figure 19), all tested trajectories (from different nonzero starting points) also reached equilibrium. Multiple equilibria could occur under these assumptions in Gurtin and Levine's model, but multiple (nonzero) equilibria were not discovered in POL, though they may exist.

Under another set of assumptions (including the assumptions that g was independent of B and decreased monotonically with P, and that the mortality rate of all ages was constant), Gurtin and Levine showed that their model had exactly one stable equilibrium. This behavior may be similar to the behavior of POL in the cases where it tended to an equilibrium, since multiple nonzero equilibria were not discovered.

Under the assumptions of the last special case (including the assumption that their model had exactly one nonzero equilibrium, and this equilibrium was unstable), Gurtin and Levine showed that the equations defining their model had a nonconstant, periodic solution. This behavior also occurred in POL for some parameter values (e.g., Figure 23).

5.2.4. Shepherd and Cushing (1980)

Shepherd and Cushing (1980) argued that strong density-dependent mortality effects must exist in many fish populations because the stocks withstand fishing mortality rates 2-3 times greater than the natural mortality rates on those fish recruited to the fishery, without discernible changes in levels of recruitment. They argued that compensatory changes in mortality rates of sufficient magnitude could only occur in the first year of life. As a possible mechanism they revived the proposal that if larvae are abundant, food may be in short supply, so that the larvae grow slowly and are vulnerable to predators for a longer time, resulting in a greater cumulative mortality even if instantaneous mortality rates are unchanged. For this to work, they stated that the growth of larvae must be density dependent and the time during which the larvae are vulnerable to predators must be to some extent determined by size. Shepherd and Cushing (1980) also gave a review of studies in which density-dependent growth in some fish species was demonstrated, though no studies regarding walleye pollock were reviewed. However, Hayashi (1976) measured walleye pollock along the southern Pacific coast of Hokkaido Island, Japan, during 1958-69. Hayashi found that the mean body length of 1- and 2-yr-old pollock was negatively correlated with the population number of these cohorts caught several yr later, when they became mature enough to breed and began to be utilized by commercial fisheries in the area. This negative correlation could indicate that density-dependent growth was occurring.

Density-dependent growth of pollock was frequently observed in POL as emergent behavior (e.g., Table 55). This was apparently a consequence of the food limitation of pollock in the model. In addition, simulated cannibalism mortality accounted for much of the mortality of age-0 pollock in autumn when their growth was moderately limited by food supply; this source of mortality was to some extent determined by size. However, pollock prey switching may have caused more of the density dependence of cannibalism mortality in POL. Simulations varying the relative vulnerability to cannibalism (P_5) showed dramatic changes in population dynamics (Figure 23), indicating that cannibalism did indeed exert a definite control on simulated dynamics.

Shepherd and Cushing (1980) noted that in the northeast Atlantic many gadoid stocks (e.g., cod, haddock, saithe, and whiting) were currently exploited with fishing mortalities 2-5 times natural mortalities without any signs of imminent collapse. Natural mortality rates of pollock in the eastern Bering Sea fishery are thought to be about 0.30-0.70 $year^{-1}$ (Chang 1974:111-115). Assuming that eastern Bering Sea pollock are similar to northeast Atlantic gadoids leads to the hypothesis that the eastern Bering Sea pollock stock should withstand fishing mortality rates of about 0.6-3.5 $year^{-1}$. Therefore, the increases in simulated annual pollock catches found for F in the range 0.6-3.0 $year^{-1}$ (Figure 26) were not unreasonable. However, many important parameters in POL were estimated using data measured for Atlantic gadoid stocks such as cod, haddock, saithe, and whiting (e.g., EF, P_1 to P_3, P_7, P_{10}, P_{97}, P_{98}, P_{117} to P_{119}). The similarities in predicted reasonable fishing mortality rates may have been artificially caused by this common source of data. Greater confidence could be placed in the predictions of POL if such parameters were validated or reestimated using data actually measured for pollock, especially for pollock from the eastern Bering Sea.

5.2.5. Chang (1974)

Chang (1974) synthesized a large amount of valuable information on pollock and used this in various models. For example, the eastern Bering Sea pollock fishery was simulated using a single species Ricker (1958) type yield per recruit model with minor modifications. In this model it was assumed that natural mortality rates and growth rates were density-independent, fixed functions of age (Chang 1974:211-212). Chang used knife-edge recruitment to the fishery. On the basis of simulation with this model, Chang (1974:226-228) found that optimal yield per recruit occurred when F was in the range 0.4-0.8 $year^{-1}$ and ages at entry to the fishery were in the range 3-4 yr (equivalent to fork length at entry of about 29-36 cm, Chang 1974:table 34). Given the entry age of 2-4 yr (about 22-36 cm FL), Chang thought that F in the range 0.4-0.9 $year^{-1}$ would be best for optimal management. He noted that the size of 2-yr-old pollock (about 22 cm FL) might be too small to be commercially valuable. Chang also estimated the maximum sustainable yield (MSY) of the eastern Bering Sea pollock population using three different methods:

(a) fitting the generalized stock production model of Pella and Tomlinson (1969);

(b) using the empirical relationship MSY=0.5 x M xB_0, where M is the natural mortality rate and B_0 is the virgin (unfished) stock biomass (Alverson and Pereyra 1969); and

(c) using a stock recruitment relationship (Doi 1972).

The generalized stock production model and the empirical relationship did not take into account age specific effects (age structure). The empirical relationship was based on the assumptions (not known to be valid for pollock) that maximum sustainable yields are produced when the exploitable stock reaches a level approximately half its virgin level, and that a fishing mortality rate of F=M causes this stock level (Alverson and Pereyra 1969:1995). The method using the stock recruitment relationship did not take into account either density-dependent changes in M for the recruited population or density-dependent changes in growth in weight. Using these methods Chang estimated the MSY of the eastern Bering Sea pollock fishery was about 0.9×10^6 to 1.2×10^6 t/year.

Assuming the effective area of the pollock population exploited by the fishery is about 10^6 km^2, simulations with POL showed sustainable catches (catches without persistent fluctuations) of at least 4×10^6 to 5.7×10^6 t/year might be possible. These catches were produced with length at 50% maximum vulnerability to the fishery (P_{84}) in the range 15-20 cm FL and F in the range 1.2-2.1 $year^{-1}$. Preliminary indications were that the largest portion of these catches could be commercially usable for surimi, though only a small portion might be usable for fillets (Figures 26-28; Tables 30, 32, 34, and 36). Even larger average annual yields were also simulated using other combinations of F and P_{84}, but with large persistent catch fluctuations.

There were wide differences between Chang's estimates of MSY and the estimates of sustainable yield using POL. These differences apparently resulted because the models Chang used either did not include age structure or did not include density-dependent changes in processes such as growth, recruitment, or natural mortality. Such factors may be important when food-limited, cannibalistic fish are heavily exploited. Although it may eventually be confirmed that Chang's estimates of MSY were too low, his work is a good example of how simplistic nonmechanistic simulation models can still provide useful guidance in data collection and synthesis, and stimulate further research.

5.2.6. Laevastu and Larkins (1981)

Laevastu and Larkins (1981) described a deterministic multispecies model (hereafter called Laevastu's model) of the biomasses of species or ecological groups in the Bering Sea or Gulf of Alaska. In 1 example (Laevastu and Larkins 1981:table 5), 23 species or ecological groups were simulated, and 1 species could also be divided into 4 age-classes. Age-classes were additionally considered to be size-classes. One version of Laevastu's model (PROBUB) divided the Bering Sea and Gulf of Alaska into nine fisheries management and statistical areas to simulate geographic variability and migrations. Another version of the model (DYNUMES) used a computational grid covering most of the eastern Bering Sea to simulate effects of advection and migration in more detail. The standing stocks of phytoplankton and zooplankton were modeled as fixed seasonal functions of time (Laevastu and Larkins 1981:70), and therefore could be considered driving (forcing) functions. Laevastu's model was generally calibrated (tuned) by using the biomasses of apex predators (e.g., marine mammals and seabirds) as driving functions; other components of the simulated ecosystem were iteratively adjusted to levels adequate to provide the food requirements of these apex predators under equilibrium (stationary) conditions, as well as provide for a fishery and other sources of consumption. Equations in the model were generally solved using a finite difference approach with a fixed time step of 1 mo, although in some circumstances a shorter time step was used.

Laevastu's model included processes of

(a) biomass growth as affected by various environmental factors (including ambient temperature), and the availability of food (and the consequent possibility of starvation);

(b) diet selection and food uptake, computed by food item, and consequent predation mortality;

(c) other mortality components, such as mortalities due to spawning stress, senescence, disease, and starvation;

(d) spawning and larval recruitment;

(e) advection and migration (from grid point to grid point); and

(f) fishing and consequent fishing mortality.

These processes were determined in terms of the entire biomass of an ecological group, species, or age-class. This was essentially equivalent to one state variable (biomass) for each entity modeled. This enabled less detailed modeling of age- and size-specific processes than in POL, which included three state variables (population number, individual body weight, and fork length) for each age-class of pollock. However, POL did not include as many species as did Laevastu's model. Unlike POL, more than one geographic region was included in Laevastu's model. Methods used to simulate biomass transfer from one age-class to the next in Laevastu's model were not described.

In feeding mechanisms in Laevastu's model, an upper limit was placed on the consumption of a given prey item--if the consumption of a prey item in one time step exceeded a predetermined maximum allowable fraction of its biomass, the consumption of that prey item during the next time step was reduced. If a predator biomass did not meet its food requirements by substitution of other prey items, the increase rate of that biomass was slowed or even reversed so that it began to decrease.

Recruitment in Laevastu's model was constrained so that biomasses remained "close" to their predetermined equilibrium biomass. This was done by making the biomass growth rate of "species" i directly proportional to $(B_{e,i}/B_{i,t-1})^{0.5}$, where $B_{e,i}$ was the equilibrium biomass, and $B_{i,t-1}$ was the biomass of species i in the previous time step.

Laevastu and Larkins (1981) realized that actual biomass distributions as a function of age may change with the intensity of a fishery, and as a result, a measured biomass growth coefficient can increase due to selective removal by the fishery of older, slower growing fish. They thought that detailed computations of such a change were not practicable in their model, but proposed the use of an approximation. However, this approximation was not used, but instead adjustments were made for individual species and specific fishing intensities (T. Laevastu, Northwest and Alaska Fisheries Center, 2725 Montlake Blvd. E., Seattle, WA 98112; pers. commun., 1982).

In the described simulations, age structure was not used in Laevastu's model, except for one species in some cases. Consequently, changes in processes thought to depend on the age or size structure of the species biomass, but not solely on total species biomass or a fixed fraction of individual body weight, instead must have been represented by empirical approximations. By implication, the underlying age structures of the simulated biomasses were fixed or limited to structures compatible with the approximations. Consequently, the range of possible dynamics of the model was limited to those phenomena which could be simulated using essentially static age structures. Some examples of important age-structure dependent processes which must have been approximated are prey selection and consequent predation and cannibalism mortality rates (dependent on the size of both predator and prey--e.g., Ursin 1973); food conversion efficiencies or food requirements for respiration and growth (even if measured as a percentage of body weight required daily--e.g., Daan 1973: table XIV, and Jones and Hislop 1978:eq. 6 and 7); individual fish maturity (e.g., Smith and Bakkala 1982:fig. 34); starvation mortality (e.g., Ivlev 1961:fig. 54-55); changes in biomass growth rates resulting from the selective removal of older, slower growing fish by a fishery; advection or migration; and the consequences of environmental anomalies.

It was possible to fit Laevastu's model to different equilibrium conditions. Because of the simplifications used in the model (for example, limitation of the total rate of consumption of a prey item to less than approximately a fixed fraction of its biomass, placement of bounds on recruitment to cause a tendency towards a predetermined equilibrium, and lack of explicit age or size structure for most modeled biomasses), it is probably best suited to simulate ecosystem dynamics close to the predetermined equilibrium. The greater the changes (perturbations) in these conditions, the greater the likelihood that some process left out or approximated could cause significant departures from reality. An example of this might be a large change in maximum fishing mortality rates or the vulnerability curve of the present pollock fishery (so that historical data are inappropriate for model calibration), bringing about a significant change in the size structure of the pollock population. This could change the size structure of other populations via mechanisms such as size-dependent predation by and on pollock, which could significantly alter natural multispecies dynamics away from the dynamics of a model in which most populations lack age structure. Since age structure is a manifest and significant characteristic of animal populations, and was shown by this study to have a significant effect on possible population dynamics, it is reasonable to include age structure considerations explicitly in ecological analyses.

Although POL used a detailed age structure for pollock, it was limited by other simplifications used. For example, most other species in the ecosystem were not modeled. This could cause its predictions of the consequences of large perturbations in the fishery (such as in Figures 26-28) to be inaccurate. Laevastu's model and POL possibly could be used to complement each other. Though lacking age structure for most modeled populations, Laevastu's model appears suited to simulate effects related to geographical variation, transportation, and multispecies dynamics. An exception is interactions involving feedback with phytoplankton and zooplankton, since these were driving functions in Laevastu's model. The model POL focuses on the age and size structure of a single species, walleye pollock, and on its food supply. Consequently POL is suited for an examination of the dynamics arising from this age structure or interactions with animals lower on the food chain (phytoplankton, copepods, and euphausiids). However, the realism of the simulated interactions with plankton may also be limited by the simplicity of the plankton submodels used--for example, the plankton submodels lacked age structure.

Laevastu and Larkins (1981) described the results of simulations with Laevastu's model for a large number of species and ecological groups. Some comparisons between their results for pollock and the results of POL regarding pollock are possible.

Laevastu and Larkins (1981:table 9) used PROBUB and estimated that the equilibrium biomass of pollock in the eastern Bering Sea in the present fishery is in the range $8x10^6$ to $15.2x10^6$ t, with a mean exploitable biomass of $6.45x10^6$ t. Using POL with the reference set of parameters and initial conditions, and assuming the effective area of the pollock population exploited by the fishery is 10^6 km^2, after the occurrence of stationary conditions the average total annual biomass of pollock was $6.6x10^6$ $t/10^6$ km^2 (this was calculated by averaging the total biomass on the first of the month for 1 yr). Annual minimum and maximum total biomasses were about $4.5x10^6$ $t/10^6$ km^2 (in May) and $8.3x10^6$ $t/10^6$ km^2 (in September). In the same simulation, assuming that the exploitable biomass of pollock was the biomass of pollock $\geq$2 yr old, the annual average exploitable biomass of pollock was $5.9x10^6$ km^2 (calculated by averaging the exploitable biomass of pollock on the first of the month for 1 yr). Annual minimum and maximum exploitable biomasses were about $3.8x10^6$ $t/10^6$ km^2 (in May) and $7.5x10^6$ $t/10^6$ km^2 (in

September). These average total and exploitable pollock biomass figures are somewhat less than those determined by Laevastu and Larkins.

5.2.6.1. Laevastu and Favorite (1976)--Using a preliminary version of DYNUMES, Laevastu and Favorite (1976) tentatively concluded that the fluctuations in pollock biomass in the eastern Bering Sea had a natural period of about 12 yr (for the fishery of that time), the fluctuations were caused by cannibalistic interactions between size-classes of pollock, and the fluctuations were affected by the fishery. This early version of DYNUMES included seven other ecological groups or species and three size-classes of pollock. A fixed fraction of one pollock size-class was moved to the next size-class for each monthly time step, and the diets of the ecological groups and pollock size-classes were determined using fixed food composition ratios independent of food abundance. These simplifications (and other factors) could have affected the quantitative accuracy of the estimate of a 12-yr period.

Periodogram analysis of catch and effort data from the time period 1964-80 showed evidence of a pollock population fluctuation with a period of at least 11.3 yr and perhaps greater than 17 yr (Figure 40, compare with Figures 5 and 6), but analysis of a longer time series might show a period significantly different from 12 yr. The null hypothesis that the time series consisted of white noise was rejected at the 95% level using Siegel's T_{lambda} test (Siegel 1980). Using Shimshoni's test (Shimshoni 1971), the periodogram ordinate corresponding to a period of 17 yr was found to be statistically significant at the 95% level, but the periodogram ordinates corresponding to shorter time periods were not significant even at the 50% level. Analysis of

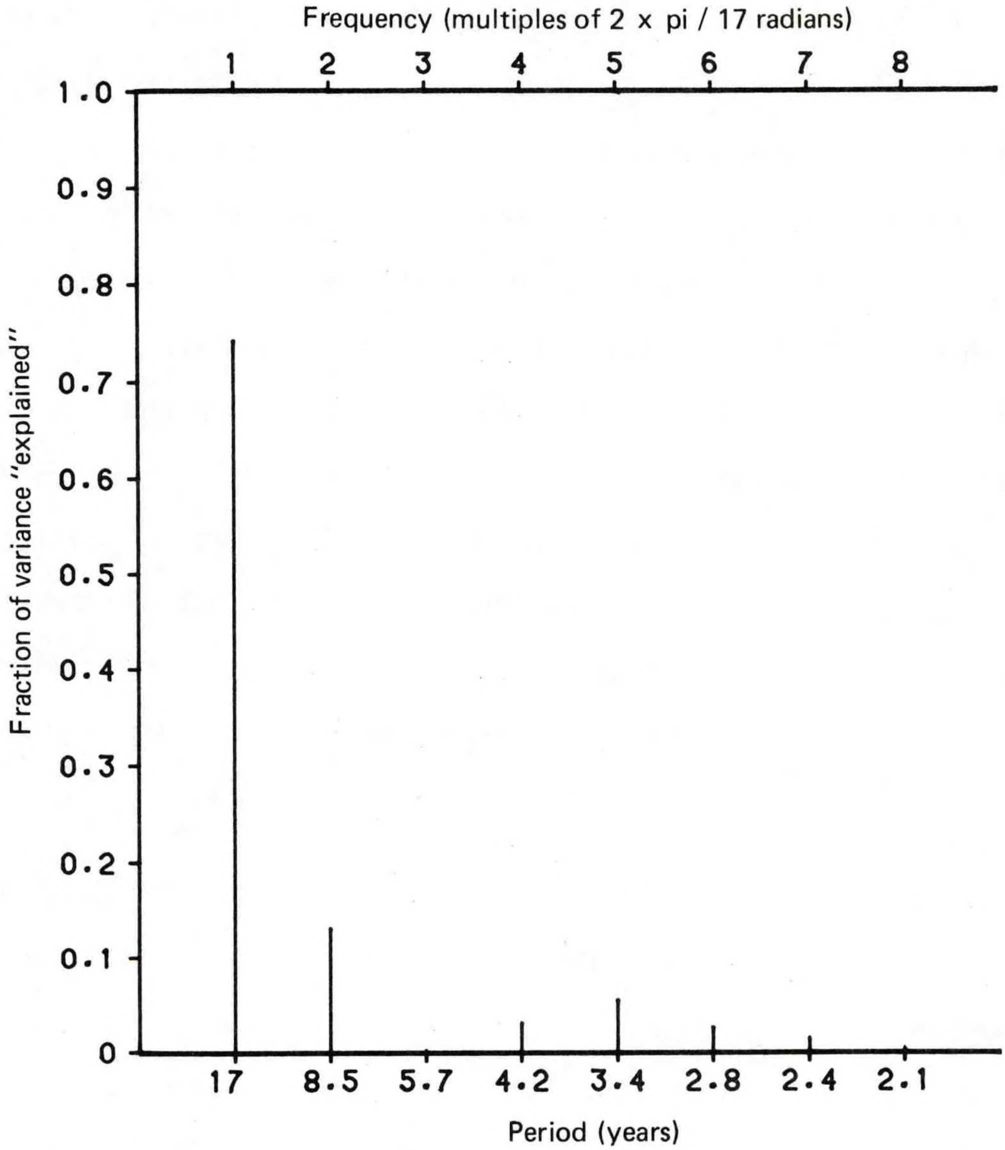

Figure 40.--Normalized periodogram of U.S. procedure CPUE for walleye pollock, 1964-80. Data values for CPUE are listed in Table 2.

a longer time series might show that some of the shorter time periods were significant. The evidence for a natural cycle lasting more than 11.3 yr was also inconclusive, despite the statistically significant results of the test, because the observed fluctuation could have been largely caused by changes (previously discussed) in the fishery during 1964-80. A much longer time series (probably more than 40 yr) is needed to empirically verify that the observed fluctuation will persist, and if it persists, to describe it statistically with confidence. One prediction from POL is that if fishery vulnerability curves and maximum fishing mortality rates remain constant at about present estimated levels, fluctuations will not persist and the pollock population will tend to equilibrate (Figure 27, Table 36), unless perturbed by factors not simulated (e.g., temperature anomalies, serious underreporting of catches, or multispecies interactions other than with plankton).

5.2.6.2. Laevastu and Marasco (1982)--Laevastu and Marasco (1982) reviewed and discussed evidence concerning the existence, nature, and consequences of fluctuations in fish stocks.

They also simulated stock fluctuations in the eastern Bering Sea and Gulf of Alaska using the multiple species model PROBUB. They assumed there was no immigration and emigration between regions simulated. Apparently, explicit age structure (i.e., more than one age- or size-class for any species) was not used in the simulations described. The fluctuations simulated apparently resulted from the multiple species nature of the model, and not from a variable age structure. They found that the pollock biomass fluctuated with a typical mean period of about 5 yr, which seems comparable to the dominant period of persistent fluctuations in pollock catches for some combinations of

F and P_{84} used in POL (Table 42), though the fluctuations in POL did not persist for other combinations. Age structure played an important role in the dynamics of fluctuations in POL, but multiple species (except phytoplankton, copepods, and euphausiids) were not included. Laevastu and Marasco (1982) thought that heavy fishing would lower adult biomasses and decrease the magnitude of fluctuations. Simulations with POL indicate that fishing would need to be quite heavy before the magnitude of fluctuations would be dampened by increases in F; for a given value of P_{84}, increases in F to as much as 3.0 year^{-1} did not decrease the magnitude of fluctuations of pollock catches (Table 36), although a minor exception occurred in the case P_{84}=25 cm, when F was increased from 2.7 year^{-1} to 3.0 year^{-1}.

5.3. Suggestions for Future Studies

5.3.1. Further Simulation of Consequences of Fishery Management Policies

Consequences of a number of different fishery management policies could be predicted using the present version or simple modifications of POL. Some examples are the effects of a seasonally varying fishery, different levels of maximum fishing effort, pulse fishing, constant quotas of pollock, minimum size requirements for pollock used in processing machinery, and different fishery vulnerability curves (for example, resulting from targeting on medium-size pollock for surimi to the partial exclusion of larger pollock).

Economic factors may result in important constraints on optimum yields of pollock (Wespestad and Terry in press), and could be simulated in POL by including cost functions for fishing effort and price functions (perhaps depending on individual pollock lengths and weights) for the pollock catch.

Simulations of risk could be performed by inclusion of "random" elements in the model and performance of replicate simulation runs, though this could be expensive in computer time. The elements varied might also have partial autocorrelations in addition to a random component. For example, some components of pollock mortality could be varied at predetermined intervals (perhaps once per simulated year) by changes in appropriate parameters (EF, array M, P_{97}, P_{98}). The magnitude and timing of the seasonal pulses of primary carbon production could also easily be varied by changing the appropriate parameters (P_{21} through P_{31}) at predetermined time intervals. The inclusion of stochastic elements would make possible testing different strategies to harvest optimum yields of pollock when pollock population fluctuations have a random component; examples of such strategies are described by Ludwig (1980).

5.3.2. Further Sensitivity Analysis of POL

As previously discussed, the values of a large number of parameters appeared sensitive in model exercises or model calibration (see lists in Section 5.1.2) and could be further studied. In addition, small changes in the values of some of the following parameters also might significantly alter model dynamics; at least preliminary sensitivity analyses should be done in most cases. The parameters are: the timing of discrete time events (array TEV), pollock egg mortality rate (parameter EF), the population level at which extinction was considered to occur (NMIN), pollock respiration (P_1, P_2), pollock food conversion efficiencies (P_3, P_{117}, P_{118}), pollock spawning parameters (P_6, P_{20}, P_{62}, P_{107} to P_{110}), initial length of larval pollock (P_{14}), parameters governing primary production of carbon (P_{21} to P_{26}, P_{28} to

P_{31}), other parameters governing the plankton populations (P_{40} to P_{42}, P_{44} to P_{46}, P_{48}, P_{52} to P_{56}, $ZLNG_2$, $ZLNG_3$, ZW_2, ZW_3), pollock prey selection (P_{59}, Q2), direct consumption of phytoplankton by pollock (P_{60}, ZW_1), condition index of pollock less than P_4 in length (P_{63}, P_{80}), condition index of large pollock (P_{70}), vulnerability (recruitment) of pollock to being cannibalized (P_{65}, P_{66}), pollock prey switching (P_{67}), immigration of cohort 1 pollock (P_{74}, P_{75}), steepness of the vulnerability curve to the fishery (P_{85}), the rate of growth in length of larval and juvenile pollock (P_{91} to P_{93}), and the rate of growth in length of older pollock (P_{99}, P_{100}).

The sensitivity of the model to the values of parameters which determine starvation mortality among cohort 1 pollock (P_{81} to P_{83}) may be worth studying for some combinations of parameters, although it appears unnecessary for the reference set. This is because starvation (condition-dependent) mortality did not occur among cohort 1 pollock using the reference set of parameters and initial conditions. It also was not observed to occur in this cohort in any other simulation where P_5 (relative vulnerability to cannibalism) equaled 1. However, to reduce the amount of paper needed for simulation exercises, data on starvation mortality was frequently printed for only one date per simulated year, so it is possible that unobserved starvation mortality did occur in some cases. Starvation mortality did occasionally occur among cohort 1 pollock when no cannibalism was allowed (P_5=0).

5.3.3. Further Data Collection and Analysis

Sensitivity analyses already performed with POL show the need for further data collection and/or analyses to better estimate parameters for 1) the effective area (extent of migrations) of the pollock population utilized by the fishery; 2) the catchability of pollock as a function of pollock length and nominal fishing effort (used to estimate fishing mortality); and 3) pollock prey selection and feeding rates (as a function of prey species, predator and prey sizes, and prey abundance) for all ages of pollock. During the fitting and validation process it appeared that data was lacking regarding prey selection, feeding rates, and respiration rates of Bering Sea euphausiids (particularly Thysanoessa spp.); statistical distribution functions for abundance estimates of phytoplankton, copepods, euphausiids, and pollock at various times of the year; feeding conversion efficiencies and respiration rates for pollock of all ages; sources and magnitudes of mortality of pollock eggs and young, including vulnerability of pollock to cannibalism as a function of changing habits with age; pollock starvation and/or spawning stress and consequent effects on mortality rates; quantitative changes in pollock feeding rates as a function of maturity and breeding behavior; the amount of energy or other resources expended by pollock in spawning; causes of variability of pollock egg fecundity; the ratio of g C to g wet weight for adult pollock; fresh wet weights of larval pollock as a function of length or age; the relationship of standard length to the total length or fork length of pollock <10 cm FL; and causes and magnitudes of error in estimating pollock CPUE.

In many cases, point estimates of parameters or population levels are published without indication of the statistical distribution or variability of the estimate. Such information on statistical distributions is needed to calibrate and validate models such as POL. One way to provide this information is to make available the "raw" data used in making the estimates. Another way to provide the needed information is to examine the raw data and select an appropriate statistical distribution function describing any unexplained or random variability; the parameters of this distribution function can then be estimated and published. If the data are found to be normally distributed, then publication of the sample mean, sample variance, and number of observations is sufficient. If the data are found to be well-described by a linear regression model with normal errors, it is not sufficient to merely publish the usual regression coefficients, number of observations, correlation coefficient, and residual variance. It is also necessary to publish additional information contained in either the variance-covariance matrix or the $(X'X)^{-1}$ matrix, where X is the data matrix of the independent variables and X' is the transpose of X (e.g., see Draper and Smith 1981:70, 94). In the case of a least squares linear regression with one independent variable, this is equivalent to publishing the sample mean of the independent variable in addition to the more usual statistics already mentioned. This information is essential to calculate confidence intervals for values of the dependent variable predicted from values of the independent variables and also permits the comparison of simulated values with values calculated using the estimated regression equation.

Cohort analysis or related methods are often used to estimate actual pollock population abundances and age distributions. Consequently, for the purposes of model calibration and validation it is important to be able to easily determine the similarity between simulated pollock population abundances and abundances estimated using cohort analysis. A cohort analysis could be performed using the method of maximum likelihood described by Fournier and Archibald (1982). Simulated pollock catch-at-age data could then be substituted for the so-called true (actual) values which were found to maximize the likelihood function used by that method. The resulting value of the likelihood function could be easily compared to the maximum value which had been found in performance of the cohort analysis, perhaps by using a generalized likelihood-ratio test (see Mood et al. 1974:440-441). This would provide a measure of the similarity between the simulated data and the cohort analysis estimates. The method of Fournier and Archibald has the additional advantage of permitting the incorporation of information about the statistical uncertainty of measured quantities such as ages, catch at age, and natural and fishing mortality rates.

Frequently CPUE indices are published without any indication of their statistical distribution. When such an index is used to estimate historical effort levels (as was done in this study), information on the statistical distribution of historical catches and corresponding CPUE indices is needed to develop confidence intervals for estimated effort and resultant fishing mortalities. More generally, CPUE indices are often used by fishery managers to assess whether a stock is overfished. The statistical distribution of an index can be used to calculate confidence intervals; the statistical distribution is necessary to determine how much confidence can be placed in a given index. Too much reliance on a point estimate of a CPUE index with a wide confidence interval could conceivably lead to a stock crash. A given CPUE index could also be unreliable if the population model implicit in its use is mostly invalid.

5.3.4. Evaluation of Computer Aided Methods of Model Calibration

POL is a nonlinear model. Because of this, parameter estimation was difficult and complex; it took more than a year to arrive at the present reference set of parameters. If a sensitive parameter value is changed to take into account an improved estimate, in some cases it might take weeks or months to recalibrate and revalidate POL. This limits the usefulness of POL and similar models; methods to speed up the calibration process could be very valuable.

Many parameter estimation methods to calibrate nonlinear models require repeated calculation of a gradient (i.e., vector of partial derivatives) of an objective function with respect to the model parameters being estimated. Unfortunately most elements of such a gradient would be difficult or impossible to calculate analytically for POL. An alternative is to calculate the gradient by numerical approximation, but this would probably require that the state variables (i.e., variables defined by differential equations) used in the objective function be determined to a high degree of accuracy, more than the approximately two significant digits of accuracy presently used in POL. Because the state variables of POL are determined using numerical integration, the repeated calculation of state variables to a high degree of accuracy to fit the model would be extremely expensive in terms of the computer time required. The following two-stage fitting process might lessen this difficulty by avoiding numerical integration of model differential equations during the first stage.

In the first stage, the derivatives of the state variables (with respect to time) which are explicitly calculated in POL would be fit to corresponding derivatives calculated from actual "smoothed" data, in a manner similar to a procedure suggested by Varah (1982). This is described below.

Simple, differentiable functions would be fit to actual data (perhaps after an appropriate transformation) measured for trajectories of the state variables as a function of time. Varah suggested the use of cubic spline functions fit using interactive graphics. However, pollock lengths could instead be determined using a fitted von Bertalanffy growth curve or some other differentiable growth curve, and pollock weights could be determined using fitted allometric length-weight relationships. Pollock cohort population numbers might be appropriately represented by an exponential function of cubic spline functions which had been fit to logarithms of the population numbers.

These simple functions for trajectories of state variables would be used in two different ways. First, the functions would be evaluated at given times and their values used in place of the state variables in the differential equations defining POL to generate a set of derivatives called model-generated derivatives. Second, the derivatives of the functions would be evaluated at those same given times to produce another set of derivatives called fitted function derivatives.

The differences between the model-generated derivatives and the fitted function derivatives (as measured by a suitable objective function discussed below) would be minimized by adjusting the model parameters. A number of different numerical minimization algorithms might be applicable if modified to use numerical approximation of the gradient of the objective function with respect to model parameters. Some examples are algorithms based on the formula of Broyden, Fletcher, Goldfarb, and Shanno (Fletcher 1980:eq. 3.2.12), and Levenberg-Marquardt methods (Fletcher 1980:section 5.2). Methods of constrained optimization could also be used. Interval analysis methods might be usable to assure finding the global minimum of the objective function (Hansen 1980; Hansen and Sengupta 1980).

Validation exercises after completing this first stage might show that the resulting parameter estimates were adequate. If not, a second stage could be used. In this stage, repeated simulations using numerical integration of the model equations would be performed, with parameters and initial conditions being adjusted to improve model goodness-of-fit. This could be done subjectively, or by using a gradient-free "evolution" strategy discussed in Schwefel (1981), where model parameters or initial conditions are randomly varied, but information derived from previous choices is retained and used to accelerate convergence. Because numerical integration of the model equations would be required in the second stage, it would probably be expensive in computer time.

A difficulty in either the first or second stage is the choice of an objective function to measure the deviation of model-generated values from the fitted function derivatives (stage 1) or data values (stage 2). Varah (1982:eq. 2.1) suggested the residual sum of squares. A difficulty in the use of this objective function arises because of the different nature and units of state variables in models such as POL. For example, for pollock >2 yr old a residual of 10 g/year (resulting from a derivative of pollock weight) is probably of lesser importance than a residual of 10 cm/year (resulting from a derivative of pollock length). However, simple calculation of the residual sum of squares would give equal weight to both residuals. An objective function based on weighted residual sums of squares (perhaps weighted by the reciprocals of standard deviations calculated from the original data or by using subjectively chosen weights) might solve the difficulty. An objective function based on maximum likelihood (e.g., Mood et al. 1974:chapter 7, section 2.2) also might solve this difficulty.

5.3.5. Further Improvements and Extensions of POL

5.3.5.1. Further Model Calibration--The fit of POL can be improved in those areas (such as the weight of larval pollock) found to have significant lack-of-fit in validation exercises. Improved parameter values and modified equations could also be incorporated as new data become available.

5.3.5.2. Improved Method of Numerical Integration--A better method of numerical integration could probably be found to use in POL. A numerical integration subroutine (DASCRU) similar to the Runge-Kutta Merson method used in POL was criticized by Enright and Hull (1976:955-956) as being unreliable for nonlinear equations, especially with stringent error tolerances. However, stringent error tolerances were not used in simulations with POL. As an additional accuracy check, simulation experiments were performed with special cases of parameter values so that values of model state variables could be calculated analytically, independently of the numerical integration of the differential equations of the model. For example, parameters equivalent to the analytic Beverton and Holt (1957) yield per recruit model were used in one case. In all cases, the values of the state variables calculated using numerical integration agreed with the values analytically calculated, within the limits of accuracy of numerical integration (at least two significant digits). This verified that the numerical integration subroutine was sufficiently accurate, as well as providing evidence that the computer program correctly implemented the model. Nonetheless, other numerical integration subroutines, such as DERKF or DEABM discussed by Shampine and Watts (1980), may be faster than the present numerical integration subroutine, as well as being more reliable for stringent error tolerances. Numerical integration subroutines are being developed which automatically locate and efficiently cope with jump discontinuities in first or higher order derivatives (H. Watts, Applied Mathematics Division 2646, Sandia National Laboratories, Albuquerque, NM 87185; pers. commun., 1982). Such a subroutine might also be significantly faster and more accurate than the present subroutine. The use of POL was expensive in computer execution time (central processor time) which was devoted to numerical integration and evaluation of derivatives; a better numerical integration subroutine might decrease this cost.

5.3.5.3. Inclusion of Temperature Effects--Terms to account for the effects of environmental temperature changes could be included in equations determining feeding rate, respiration, and mortality. If temperature changes with time were modeled as a driving function with a stochastic component, an assessment could be made of the effect on pollock population dynamics (for example, the risk of a stock crash in a simulated fishery) due to temperature changes.

5.3.5.4. Improvement of Plankton Submodels--As discussed previously, the plankton submodels used in POL were quite simple, since all the individuals in each major group (phytoplankton, copepods, and euphausiids) were assumed to have the same size. More detailed, size-structured submodels (especially of zooplankton) might significantly improve the realism of the modeling of cohort-1 (age-0) pollock, because this cohort only consumed zooplankton in simulations in this study. Since cohort-1 pollock can be a major prey item of older pollock in the model, the realism of the simulation of older pollock might also be significantly improved.

The inclusion of zooplankton or other predators which feed on pollock eggs or young could cause a feedback loop with interesting dynamics, if the zooplankton or other predators in turn were fed upon by larger pollock.

5.3.5.5. Multispecies Model Extensions--The model POL (or a similar model) could be extended to include other species which might interact with pollock. Some examples are fur seals and other marine mammals, sea birds, squids, Pacific cod (*Gadus macrocephalus*), Pacific herring (*Clupea harengus pallasi*), crabs, and shrimps.

5.3.6. Applicability and Validity of Different Models or Modeling Approaches

The model of Andersen and Ursin (1977) is a multispecies, age-structured model which could possibly be adapted to the Bering Sea. The model of Getz and Swartzman (1981), based on a Markov probability transition matrix to simulate a stock-recruitment relationship, could possibly be modified to model the risk of a stock crash in different pollock fisheries, though existing data might be insufficient to estimate the probability transition matrix with much precision. Continued use and further extension of the PROBUB and DYNUMES models described by Laevastu and Larkins (1981) should prove fruitful.

The model POL, and the models described by Laevastu and Larkins (1981), Andersen and Ursin (1977), and Getz and Swartzman (1981) seem limited by either the amount of computer time or memory available. If some other modeling approach might be less limited by computer time and memory constraints, its applicability to the simulation of the eastern Bering Sea ecosystem and fisheries should be investigated. An example might be the use of the particle-in-cell approach to simulation of the survival of pollock eggs and larvae, which was discussed by Walsh et al. (1981). An attempt could be made to fit an autoregressive integrated moving average (ARIMA) model to monthly pollock CPUE indices. Such a model might be especially useful for short-term forecasts up to about 1 yr in advance (Saila et al. 1980). Other simple models seem to be useful for short-term forecasts in some fisheries (Stocker and Hilborn 1981) and might be useful in the eastern Bering Sea pollock fishery. Simple models can also be useful when calibrated to well-validated mechanistic models. However, simple statistical or heuristic models may oversimplify the natural system being modeled, so that little or no insight is given into processes which may cause complex dynamics, such as different regimes of dynamic behavior. For such purposes, more simplistic descriptive models cannot be substituted for more detailed mechanistic models.

5.3.7. Applicability of Simulation Languages

In this study, years were spent to program the computer implementation of the model, find and correct programming errors, and to graphically and statistically analyze model input and output data.

A good simulation language might significantly speed up the programming, error detection and correction, and model modification process. For a model such as POL, the language would have to be capable of handling mixed discrete and continuous event simulation. The language would also have to be capable of scheduling events according to many different "clocks" or cycles. For example, clocks explicitly or implicitly simulated in POL included ordinary continuous chronological time, the season of the year, the time in the cycle of performance of discrete time events, and the pollock life cycle (age of each pollock cohort). To handle special situations, it would be desirable that user-provided subroutines for numerical integration could be substituted for the subroutines provided in the language. It would be desirable that the language compiler produce fast-executing programs with near optimal usage of computer central memory, since many model implementations seem to be limited by computer execution time (POL is an example) or by computer memory capacity. It would be desirable that the language provide a simple interface with computer data storage and retrieval (data base) utilities, and statistical analysis and computer graphics programs. In some form, these capabilities were extensively used in the development, analysis, and communication of results of POL--improvements in the ease of usage of these capabilities would speed up the modeling process.

5.3.8. Possibility of Experimental Increases in Pollock Catch Quotas

If further research and simulation verifies that annual pollock catches can indeed be increased, larger annual quotas of pollock could be allowed on an experimental basis. It might also be necessary to set minimum quotas of small-sized pollock in order to prevent large-scale fluctuations in catches. However, because of the uncertainties in the "best available knowledge" (e.g., many important parameters in POL were estimated for species other than pollock), immediate large changes in the present fishery might not be prudent. In any fishery management analysis, it is desirable to confirm or validate all results with other methods, particularly if the results are radical or counterintuitive. If changes are eventually made, a gradual approach over a period of years is suggested so that actual consequences to pollock stocks and the eastern Bering Sea ecosystem can be assessed, which should improve the probability of detecting any unforeseen damage before serious harm is done.

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APPENDIX A

CRITERION FOR A STATIONARY DISTRIBUTION

A stationary distribution (the occurrence of stationary conditions) was assumed to have resulted in the model if the values of all state variables (those variables determined by numerical integration of differential equations, and also the total number of pollock eggs surviving to hatch) at the instant before cohort update were essentially equal to their values at the time of the previous cohort update. A small tolerance was allowed for slight errors in numerical integration. A stationary distribution was assumed to have occurred if each state variable satisfied the inequality

$$ABS(B_i - AC_i) < R_i, \tag{11}$$

where ABS is the absolute value function, B_i is the i'th state variable, AC_i is the value of the i'th state variable at the time of the previous cohort update, and R_i is determined by the relation

$$R_i = \begin{cases} 2 \times ACCRCY, \text{ if } ABS(B_i) < 10^{-5} \\ \\ 2 \times ACCRCY \times ABS(B_i), \text{ if } ABS(B_i) \geq 10^{-5}, \end{cases} \tag{12}$$

where ACCRCY is the accuracy tolerance used for numerical integration (equal to 0.005 for the reference set of parameters). For the reference set of parameters, this essentially meant that if each state variable was within approximately two significant digits of its value the previous year at cohort update time, stationary conditions were assumed to have occurred. The criterion for a stationary distribution was satisfied in the simulations described in this study if every state variable was periodic with a period of 1 yr. The criterion for a stationary distribution could also have been satisfied if the state variables took on the values of the previous year at the time of each cohort update, even if they deviated at other times of the year. However, this probably never occurred.

In this study, if the criterion for a stationary distribution was satisfied before the scheduled end of a simulation, then the simulation was allowed to continue only about two additional simulated years before being stopped. This early termination was performed to reduce computer costs.

APPENDIX B

COMPUTER WORD SIZE USED IN SIMULATIONS

The computer program used to implement POL was written in FORTRAN IV, and compiled and run on Burroughs B6800 and B7800 computers. The program used single precision variables and arrays. A single precision real number was represented by a 39 bit mantissa and 6 bit exponent, with two additional bits used for the sign of the mantissa and the sign of the exponent. A single precision integer was represented by 39 bits, with 1 additional bit used for its sign (Burroughs 1978:chapter 11). Double precision variables or arrays were not used.

APPENDIX C

LISTING OF FORTRAN IV COMPUTER PROGRAM FOR POL

```
$SET LIST $ XREF
C- MAIN PROGRAM POLSIM (JULY 1983): SIMULATES A POLLOCK POPULATION
C- USING A POPULATION AND BIOMASS COHORT MODEL NAMED POL. PROGRAMMED BY
C- C.D. KNECHTEL, MODIFIED AND EXTENDED FROM PROGRAM BY L.J. BLEDSOE.
C- SUBROUTINE MERSON IS USED AS AN ORDINARY DIFFERENTIAL EQUATION SOLVER
C- TO INTEGRATE DIFFERENTIAL EQUATIONS. MERSON WAS MODIFIED FOR POL.
$SET ERRLIST LINEINFO LIMIT=10
$SET OPT=1 B7700
$RESET FREE
C- DATA DUMP FILE (EACH RECORD MAY CONTAIN UP TO 77 CHARACTERS):
FILE  4(KIND=DISK,MAXRECSIZE=14,BLOCKSIZE=420,TITLE="DD.",AREAS=80,
     -AREASIZE=1020,SECURITYTYPE=PUBLIC,SECURITYUSE=IN,INTNAME="4.")
C- FILES 5 AND 6 ARE INPUT AND PRINTOUT FILES:
FILE  5(KIND=DISK,FILETYPE=7,TITLE="L/D/DATA.",INTNAME="5.")
FILE  6(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,INTNAME="6.")
C- FILE WITH DATA IN APPROPRIATE FORMAT FOR RESTARTING SIMULATION RUN:
FILE  7(KIND=DISK,MAXRECSIZE=14,BLOCKSIZE=420,TITLE="D/OUT.",
     -INTNAME="7.")
C- A PRINTER FILE DESCRIBING PARAMETERS USED IN MAKING GRAPHS:
FILE  8(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,INTNAME="8.")
C- JOB SEQUENCE NUMBER FILE:
FILE  9(KIND=DISK,MYUSE=IO,FILETYPE=7,TITLE="L/SEQ.",EXCLUSIVE,
     -UPDATEFILE,INTNAME="9.")
C- FILES 11-17 ARE USED FOR MAKING GRAPHS - ALL NEED NOT BE USED
FILE  11(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="11.")
FILE  12(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="12.")
FILE  13(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="13.")
FILE  14(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="14.")
FILE  15(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="15.")
FILE  16(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="16.")
FILE  17(KIND=PRINTER,BLOCKSIZE=133,UNITS=CHARACTERS,PAGESIZE=66,
     -INTNAME="17.")
CDC: THE ABBREVIATION CDC REFERS TO CONTROL DATA CORPORATION COMPUTERS.
CDC   OVERLAY (P,0,0)
CDC   PROGRAM POLSIM(INPUT=/80,OUTPUT =/137,PUNCH=/80,HARDPR=/137,
CDC  & TAPE5=INPUT,TAPE6=OUTPUT,TAPE7=PUNCH,TAPE8=HARDPR)
```

```
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT,  ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/AGEC"
      COMMON /AGEC/ IAKE,AC(67)
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      DATA KE,FCF,FCM,FSTART,STPRNT,VCUM,GCN/-1,40*-1.,-1.,3*0.,20*0./
      DATA TPOFF,ASTOP,IAKE,IERTOT,RQMAX,AC/-1.,.FALSE.,0,0,0.,67*0./
C  THE BELOW IS NEEDED FOR THE DOBEV OPTION:
      DATA SM /20*0./
      NAMELIST /INTERR/ IERTOT,RQMAX
C///////////////////////////////////////////////////////////////////////
C
C     CALL SUBROUTINE TO INPUT PARAMETERS AND INITIAL CONDITIONS.
      CALL INPUTR
CDC      CALL OVERLAY (1HP,1,0)
C     CALL ROUTINE TO INITIATE REPEATED SIMULATION
      CALL SIM
CDC      CALL OVERLAY (1HP,2,0)
CDC   IF (RQMAX.LE.0.) STOP "NORMAL"
      IF (RQMAX.LE.0.) CALL MSTOP( "NORMAL" ,6)
C
C///////////////////////////////////////////////////////////////////////
CDC THE FOLLOWING STATEMENTS INSURE CERTAIN EXTERNALS GET
CDC LOADED ONTO THE (0,0) OVERLAY WHEN USING A CDC COMPUTER.
      WRITE(6,INTERR)
C- RQMAX IS THE MAX FOR THE ENTIRE SIMULATION RUN OF THE ESTIMATED
C- RELATIVE INTEGRATION ERROR FOR ANY VARIABLE (SEE SUBROUTINE DETECT).
      CALL MSTOP("INTEGRATION ACCRCY ERRS,TOTAL=IERTOT",36)
CDC   TL=TL**1.1
CDC   STOP"INTEGRATION ACCRCY ERRORS,  TOTAL=IERTOT"
      END


      SUBROUTINE MSTOP(STRNG,NCHAR)
C* PRINTS A MESSAGE, THEN STOPS THE COMPUTER RUN.
```

```
C* THE MAX DIMENSION FOR STRNG THAT WOULD WORK ON THE B6800 WAS 6.
      DIMENSION STRNG(6)
      J=(NCHAR+5)/6
      WRITE (6,10) (STRNG(I),I=1,J)
 10   FORMAT (/1X,4HSTOP , 1X,1H",6A6,1H")
      STOP "MSTOP"
      END


      SUBROUTINE WPARS
C- WRITES OUT THE PARAMETERS
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
$INCLUDE "L/I/NAME"
      NAMELIST/ISVN/MT,RC,FD,ICANDQ,ICANFQ,IDOF,IEXIST,NOCOH,ZM,FCF,FCM,
     -EATER,LAYING,RIPEN,FDU,HLCAND,YT,CT,FSTART,FISHIN,SM,WL,CN,ICANAQ
      NAMELIST/PARP/P
      NAMELIST/PARS/KAY,D2,D4,D7,D8,NMIN,PLENTY,Q2,ZLNG,ZW,EF,M,F,
     -FISHIN,FSTART,ICANE,EGGDUR,WOO,HOMAX,PREDUR,AOFF,EATER,FCF,FCM
      NAMELIST/CTRL/NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,TDL,IERTOT,RQMAX,
     -COMAX,CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV,TEV,NXTEV,NGR,IGR,DOGRPH,NOCUM
      NAMELIST/CTRLRD/TF,TL,STPRNT,STPNCH,DD,PCHEND,DOBEV,RDWGHT,TP,
     -TPOFF,DOGRPH,SHOWB,SHOWD,DBUG,TD,TDMIN,TDMAX,ACCRCY,DTAU,NC,COMAX,
     -NVON
      WRITE (6,4) (I,I=1,10),P
 4    FORMAT(/I10,9I13/"   P = " / 20(1X,10G13.6/))
      WRITE(6,PARS)
      RETURN
      END


      SUBROUTINE INPUTR
C- READS MODEL PARAMETERS, INITIAL CONDITIONS, OR DRIVING FUNCTIONS.
CDC   OVERLAY(P,1,0)
CDC   PROGRAM INPUTR
      DIMENSION LTRAN(3)
      DIMENSION ID(14),  IDG(42),PTITLE(4)
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
```

```
      COMMON /MER/ACCRCY, IER, LIER, IERTOT, RQMAX, SHER(5, 7), TDMIN, TDIMIN,
     -TDMAX, KE, NZ, NG(67), VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAQ, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17, 20), WL(20), YT, CT, PREDUR, HOMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, COMAX, ASTOP, DD,
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
$INCLUDE "L/I/NAME"
      NAMELIST/ISVN/MT, RC, FD, ICANDQ, ICANFQ, IDOF, IEXIST, NOCOH, ZM, FCF, FCM,
     -EATER, LAYING, RIPEN, FDU, HLCAND, YT, CT, FSTART, FISHIN, SM, WL, CN, ICANAQ
      NAMELIST/PARP/P
      NAMELIST/PARS/KAY, D2, D4, D7, D8, NMIN, PLENTY, Q2, ZLNG, ZW, EF, M, F,
     -FISHIN, FSTART, ICANE, EGGDUR, WOO, HOMAX, PREDUR, AOFF, EATER, FCF, FCM
      NAMELIST/CTRL/NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, TDL, IERTOT, RQMAX,
     -COMAX, CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV, TEV, NXTEV, NGR, IGR, DOGRPH, NOCUM
      NAMELIST/CTRLRD/TF, TL, STPRNT, STPNCH, DD, PCHEND, DOBEV, RDWGHT, TP,
     -TPOFF, DOGRPH, SHOWB, SHOWD, DBUG, TD, TDMIN, TDMAX, ACCRCY, DTAU, NC, COMAX,
     -NVON
      DATA LTRAN/1HX, 6HALOG10, 3HEXP/
      CALL ITIME(IXX2, KSEQ)
CDC   CALL DATE(XX1) $ CALL TIME(IXX2)
      XX1=TIME(15)
C KD IS THE NUMBER OF DIMENSIONS OF N, W, L, NDOT, WDOT, LDOT, B, MT, SM,  ETC.
      KD=20
C     READ MODEL IDENTIFIER
      READ (5, 700) ID
  700 FORMAT(13A6, A2)
      PRINT 800,    XX1, IXX2, KSEQ, ID
  800 FORMAT( "1AGE STRUCTURED POPULATION SIMULATOR; DATE, TIME&SEQ NO="
     -, A6, I9, I6 / 1H , 13A6 , A2)
  801 FORMAT(  "AGE STRUCTURED POPULATION SIMULATOR; DATE, TIME&SEQ="
     -, A6, I9, I6 / 13A6 , A2)
      READ ( 5, /)    CYCLE,          NEV ,  (IEV(I) ,  TEV(I) ,  I=1, NEV)
C  SORT AND TRANSFORM TEV AND SET CYOFF:
      CALL SUB
      WRITE(6, 802)   CYCLE, CYOFF ,  NEV, (  IEV(I) ,  TEV(I) ,  I=1, NEV)
 802  FORMAT (" CYCLE="F9.4 ", CYOFF=" F9.4 ", NEV="I3
     &  ", (IEV(I), TEV(I)):"(/10(" ("      I2", "F7.4")" )))
C     READ SIMULATION PARAMETERS
      READ (5, CTRLRD)
      WRITE(6, CTRLRD)
      IF (DOBEV) SHOWD=.FALSE.
C- ONLY FORWARD INTEGRATION IS ALLOWED:
      TD=ABS(TD)
      TDMIN=ABS(TDMIN)
      TD=AMIN1(TD, TDMAX)
      IF (TF.LE.TL) GO TO 150
```

```
      T=TL
      TL=TF
      TF=T
 150  TP = AMAX1(AMIN1(TL - TF , TP) , TDMIN)
      IF (TPOFF.LT.0.) TPOFF=TF
      TDIMIN=TD
      IF (DOBEV) NVON = COMAX
      IF (PCHEND.AND.STPNCH.GE.TL) STPNCH=TL - TDMIN
      IF (TL.LT.STPRNT) STPRNT=TL
      IF(STPNCH.LT.STPRNT) STPRNT=STPNCH
      NOCUM=(TT.LT.STPRNT-DTAU-TDMIN) .AND. (.NOT.DD)
      IF (STPNCH.GT.TL) GO TO 165
C- ASSIGN A UNIQUE TITLE TO THE "PUNCH" FILE.
      WRITE(PTITLE,162)XX1,KSEQ
 162  FORMAT("D/OUT/",A6,1H/,I5,1H.)
      CHANGE(7,TITLE=PTITLE)
      WRITE (7,801)     XX1,IXX2,KSEQ,ID
C- ASSIGN A TITLE TO THE DATA DUMP (DD) FILE:
 165  IF (.NOT.DD) GO TO 170
      WRITE(PTITLE,167)XX1,KSEQ
 167  FORMAT("DD/",A6,1H/,I5,1H.)
      CHANGE(4,TITLE=PTITLE)
      WRITE (4,801)     XX1,IXX2,KSEQ,ID
C     READ INITIAL CONDITIONS -- STATE OF SYSTEM AT TIME TF
C- IF RDWGHT=.FALSE.,THEN INITIAL WEIGHTS ARE CALCULATED NEAR THE END OF
C- INPUTR USING FUNCTION WVB.
 170  IF (RDWGHT) GO TO 250
      READ (5,/)        E , PHY,COPE,EUPH,YLD,(N(I) , I=1,NC)
      GO TO 1000
C* FORMAT 251(INPUTR) AND FORMAT 330(PRINTR) SHOULD CORRESPOND.
 250  READ (5,251)     NC,E,PHY,COPE,EUPH,YLD,(N(I),W(I),L(I) , I=1,NC)
 251  FORMAT (12X,I3,5E13.8/3(2E10.5,F6.3),7(/3(2E10.5,F6.2)))
C
 1000 PRINT 900,TF,TL,TP,TD,NC,DTAU,DBUG    ,TDMIN,ACCRCY,RDWGHT,TPOFF,
     *COMAX,NVON,STPNCH,DOBEV,TDMAX,STPRNT
  900 FORMAT( " SIMULATION FROM"F9.4" TO "F9.4/" PRINT INTERVAL="F9.4
     >", TRIAL INTEGRATION STEP SIZE="F9.7/" NO. OF INITIAL COHORTS",
     >"--"I3/" COHORT AGE WIDTH--"F9.4/" DEBUG--"L1", TD MINIMUM="G19.14
     &", ACCURACY="G14.8",READ WEIGHTS="L1", TPOFF--"F14.9", COMAX="I3
     -", NVON="I3/" PUNCH START TIME="F9.4 ", DOBEV="L1", TDMAX="G19.14
     -", PRINT START TIME="F9.4)
      IF (TDMAX.LT.TDMIN) CALL MSTOP("TDMAX.LT.TDMIN",14)
      IF (TDMIN.LE.0.) CALL MSTOP( "TDMIN.LE.0.",11)
      TCUM=TF
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     READ PARAMETERS
      CALL PARMOD
      IF (.NOT.DOGRPH) GO TO 18
C
C* READ NUMBER OF GRAPH FILES, SCALING, AND TRANSFORMATIONS
      READ (5,/) NFILE,(SCALM(I),ITRAN(I),SCALC(I),I=1,NFILE)
C* READ LOCATIONS IN COMMON/STATE/ AND FILES FOR GRAPHING
      READ (5,/) NGR  ,(IGR(I),IFILE(I), I=1,NGR)
C READ HEADING FOR GRAPHS
      READ (5,701) IDG
 701  FORMAT (13A6,A2,2(/13A6,A2))
      LIER=1H:
      WRITE (8,800)     XX1,IXX2,KSEQ,ID
      WRITE(8,802)  CYCLE,CYOFF , NEV,(  IEV(I) , TEV(I) , I=1,NEV)
      WRITE (8,900) TF,TL,TP,TD,NC,DTAU,DBUG,TDMIN,ACCRCY,RDWGHT,TPOFF,
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     *COMAX, NVON, STPNCH, DOBEV, TDMAX, STPRNT
      WRITE(8,15) ICANF
 15   FORMAT(" FIRST COHORT WHICH MAY CANNIBALIZE IS",I4)
      IF (P(5).LE.0.) WRITE (8,25)
 25   FORMAT ( " HOWEVER, AVAILABILITY TO CANNIBALISM EQUALS ZERO.")
      WRITE (8,828) NGR, (IGR(I), I=1,NGR)
 828  FORMAT(" NO. ENTITIES GRAPHED(INCL. IN COMMON BLOCK /STATE/)=",I3/
     & " THE LOCATIONS ARE:" 32I3)
      WRITE (8,829) (IFILE(I),I=1,NGR)
 829  FORMAT (1X," GRAPHED ON FILES:",32I3)
      WRITE (8,824) IDG
 824  FORMAT ("    THE LETTERS REPRESENT:" 3(/1X,13A6,A2))
      WRITE (8,825) (I,I=10,130,10)
 825  FORMAT (" IN GRAPHS OF TRANSFORMED VALUES, COLS. 1-10=TIME."
     - /1X,13I10 /  1H ,13(10H123456789. ),2H12 /)
      DO 80 II=1,NFILE
      JFIL=II+10
      WRITE(JFIL,830)JFIL,ITRAN(II),SCALM(II),LTRAN(ITRAN(II)),
     -SCALC(II),XX1,IXX2,KSEQ
 830  FORMAT ("1FILE",I2,",  TRAN=",I2,",  ",G14.8,"*(",A6,")+",
     -G14.8," . DATE, TIME & SEQ NO=",A6,I9,I6)
      WRITE(JFIL,832) IDG
 832  FORMAT (1X,13A6,A2,2(/1X,13A6,A2))
C*    120 = 132-12 = PAGE WIDTH - SPACES FOR CARRIAGE CONTROL AND TIME:
      J=120./SCALM(II)+1.
      JDEC=MAX1(1.,4./SCALM(II)+.5)
      WRITE(JFIL,826)(IFIX(SCALM(II)*(I-1)+SCALC(II)-2.),I-1,I=1,J,JDEC)
 826  FORMAT (32(T*,I4))
      WRITE (JFIL,827)
 827  FORMAT ("+  MEASURE:"/ "      TIME:")
C* IGL DESIGNATES WHICH LINE WE ARE PRESENTLY ON IN THE FILE
      IGL(II)=6
      IHD(II)=J
      IHDEC(II)=JDEC
 80   CONTINUE
C
 18   PRINT 400
 400  FORMAT(/"1POPULATION STRUCTURE OVER TIME"
     &/" TIME, NO. COHORTS,EGGLAYERS,POINT 1ST CANN,LAST CANN,TOT POP.,
     &INITIAL EGGS,EGGS,PHYTO CARBON,COPEPODS,EUPHAUSIDS,YLD,TIME STEP"/
     &" 4( COHORT NO., NO. IN COHORT, AV. WT., AV. LENGTH)")
      IF (RDWGHT) GO TO 2000
      UD=AMOD(TF + AOFF , DTAU)
      DO 20 I=1,NC
      L(I)=0.
      W(I)=0.
      IF (N(I).LT.NMIN) GO TO 20
      W(I) = WVB(UD)
      L(I)=RLNGTH(UD)
      IF (L(I).LE.0.) CALL MSTOP( "L(I).LE.0.",10)
 20   UD=UD+DTAU
 2000 PHY=PHY*P(116)
      COPE=COPE*P(116)
      EUPH=EUPH*P(116)
      ZBS=COPE+EUPH
      E=E*P(115)
      N(1)=N(1)*P(115)
C- FDU(1) SHOULD BE PRESENTLY UNUSED, THE BELOW IS SET FOR CONSISTENCY:
      FDU(1)=P(7)
      DO 10 I=2,NC
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      N(I)=N(I)*P(115)
      FDU(I)=P(17)
      IF (L(I).LT.P(111)) GO TO 10
      FDU(I)=P(114)
 10   CONTINUE
C- THE BELOW WRITE STATEMENT MAY BE USED TO WRITE PARAMETERS IN THE
C- HEADING OF THE DATA DUMP (DD) FILE:
C-       WRITE(4,510) -9999.,KSEQ,P(5),P(84),F(1)
C- THE FORMATS LABELLED 510 IN INPUTR, ILLUS SHOULD NOT CONFLICT:
C- 510  FORMAT(3X,F11.0,I3,5E11.6)
      RETURN
      END


      SUBROUTINE ITIME(IXX2,KSEQ)
C- READ AND INCREMENT THE JOB SEQUENCE NUMBER:
      READ(9,/)KSEQ
      WRITE(9,/)KSEQ+1
C- FILE 9 IS NOT CLOSED UNTIL THE END OF THE RUN (IN SIM, CALC), SO IF
C- THE RUN ABORTS BEFORE THEN, KSEQ REVERTS TO ITS FORMER VALUE. SINCE
C- FILE 9 IS AN EXCLUSIVE FILE, ANY OTHER RUN ACCESSING IT MUST WAIT
C- UNTIL IT IS CLOSED, SO SUCH RUNS CAN ONLY RUN ONE AT A TIME.
C-    FIGURE OUT TIME OF DAY(HHMMSSFF). TIME(1) GIVES THE TIME OF DAY
C- MEASURED IN SIXTIETHS OF A SECOND:
      I=TIME(1)
      IXX2=I/216000*1000000                   %HOURS
     &    +MOD(I,216000)/3600*10000           %MINUTES
     &    +MOD(I,3600)/60*100                 %SECONDS
     &    +MOD(I,60)                          %SIXTIETHS OF A SECOND
      RETURN
      END


      SUBROUTINE PARMOD
C- READS, CALCULATES, MODIFIES, OR CHECKS VARIOUS PARAMETERS.
      LOGICAL NOUPDA
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
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```
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
$INCLUDE "L/I/NAME"
      NAMELIST/ISVN/MT, RC, FD, ICANDQ, ICANFQ, IDOF, IEXIST, NOCOH, ZM, FCF, FCM,
     -EATER, LAYING, RIPEN, FDU, HLCAND, YT, CT, FSTART, FISHIN, SM, WL, CN, ICANAQ
      NAMELIST/PARP/P
      NAMELIST/PARS/KAY, D2, D4, D7, D8, NMIN, PLENTY, Q2, ZLNG, ZW, EF, M, F,
     -FISHIN, FSTART, ICANE, EGGDUR, WOO, HOMAX, PREDUR, AOFF, EATER, FCF, FCM
      NAMELIST/CTRL/NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, TDL, IERTOT, RQMAX,
     -COMAX, CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV, TEV, NXTEV, NGR, IGR, DOGRPH, NOCUM
      NAMELIST/CTRLRD/TF, TL, STPRNT, STPNCH, DD, PCHEND, DOBEV, RDWGHT, TP,
     -TPOFF, DOGRPH, SHOWB, SHOWD, DBUG, TD, TDMIN, TDMAX, ACCRCY, DTAU, NC, COMAX,
     -NVON
      READ(5, PARP)
      READ(5, PARS)
      CALL WPARS
C CALCULATE OR CHECK CYCLE AND AGE PARAMETERS.
C  CYOFF IS THE AMOUNT OF TIME BETWEEN TIME 0 (0000 HOURS ON JAN. 1) AND
C THE LAST EVENT OF THE CYCLE WHICH CONTAINS TIME 0.  IF TIME 0
C  (0000 HOURS JAN. 1) AND THE LAST EVENT OCCUR SIMULTANEOUSLY, THEN THE
C  LAST EVENT MUST BE CHANGED TO BE THE FIRST EVENT, SO THAT CYOFF =0.
      IF (CYCLE. LE. 0.  . OR.  CYOFF. GE. CYCLE) GO TO 3000
C  THE EGG HATCH TIMES MUST BE EQUALLY SPACED IN TIME, OR AGE WILL NOT
C  BE CORRECTLY CALCULATED.  CONSEQUENTLY, CYCLE MUST BE AN INTEGRAL
C  MULTIPLE OF DTAU.
C THE LENGTH OF TIME BETWEEN THE TIMES THE EGGS ARE LAID IS THE COHORT
C WIDTH, DTAU.
      US = AMOD(CYCLE, DTAU)
      IF (US. NE. 0. ) GO TO 3000
      UC=0.
      NOUPDA=. TRUE.
      IPAIR=0
C EVEN IF THERE IS MORE THAN ONE, ALL PERIODS BETWEEN EGGLAYING AND EGG
C  HATCHING ARE CONSIDERED OF EQUAL LENGTH.  THEY MUST NOT CROSS THE
C  BOUNDS OF A SINGLE CYCLE.  THIS IS ALSO TRUE FOR ANY OTHER TIME SPAN
C  PARAMETER CALCULATED IN THE BELOW DO LOOP.
C* NOTE CHECK FOR PAIRS USING IPAIR AND POWERS OF 20 (WHICH IS THE
C* ASSUMED MAXIMUM NUMBER OF PAIRED EVENTS).
      DO 5 I=1, NEV
      UC = UC + TEV(I)
C  SEE EXPLANATION OF IEV IN ANALY
      GO TO (5, 302, 303, 304, 305, 306,  5,  5,  5,  5,  5) , IEV(I)
      CALL MSTOP ("IEV(I) OUT OF BOUNDS", 20)
 302  PREDUR = UC
      IPAIR = IPAIR+20+400
      GO TO 5
 303  EGGDUR = UC
      IPAIR = IPAIR+1-20
      PREDUR=UC-PREDUR
      GO TO 5
C   EGGDUR = AMOUNT OF TIME IT TAKES FOR THE EGGS TO HATCH AFTER LAYING.
C   PREDUR = HOW LONG POLLOCK REFRAIN FROM EATING BEFORE LAYING EGGS.
 304  EGGDUR = UC-EGGDUR
      AOFF=UC
      NOUPDA=. FALSE.
      IPAIR=IPAIR-1-8000
      GO TO 5
 305  IPAIR = IPAIR - 400
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      GO TO 5
  306 IPAIR=IPAIR+8000
  5   CONTINUE
      IF (NOUPDA .OR. IPAIR.NE.0) GO TO 2990
C  ON EXIT FROM SUB, TEV(I) IS THE TIME BETWEEN EVENT I-1 AND EVENT I,
C  EXCEPT TEV(1) IS THE TIME BETWEEN THE LAST EVENT AND THE FIRST EVENT
C  OF A NEW CYCLE.
C  THUS SUM(TEV,1,NEV) SHOULD EQUAL CYCLE.
      IF (UC.NE.CYCLE .OR. EGGDUR.LT.0. .OR.PREDUR.LT.0.) GO TO 3000
      P(103)=AMOD(AOFF+CYOFF,1.)
C-  AOFF IS USED TO CALCULATE POLLOCK AGE AS A FUNCTION OF TIME:
      AOFF = DTAU - AMOD(AOFF + CYOFF,DTAU)
C   SET OR CHECK OTHER PARAMETERS
      CALL INIT
      IF(FISHIN .AND. FSTART.LT.0.)CALL MSTOP ("FSTART NOT INPUT",16)
      IF (FSTART.LT.0.) FSTART=TF
      CALL PHYMOD
      WOO = D8*D7**D2
      IF (P(12).LT.D4) P(12)=D4
      P(77)=RLNGTH(P(12))
      IF (P(12).LE.0.) GO TO 10
      D5=WVB(P(12))
      D6=(D5-P(13))/P(12)
      D9 = (P(77) - P(14))/P(12)
  10  IF(P(65).GE.1.)CALL MSTOP("P(65) GE 1",10)
      IF (P(66).LE.0.) P(66) =RLNGTH(-P(66))
      P(65)=P(65)*P(66)
      P(66) = P(5) / (P(66)-P(65))
      HOMAX=AMAX1(P(92),P(91),P(99))
      IF (P(89).GT.P(96)) CALL MSTOP( "P(89).GT.P(96)",14)
      P(4)=(P(80)/P(70))**(1./(3.-P(63)))
      P(120)=1.-P(20)
      IF (LAYING) GO TO 14
      FCF(1)=0.
      FCM(1)=0.
C- EATER(1) IS SET IN SUBROUTINE INIT.
      DO 12 I=2,NC
      FCF(I) = 0.
      FCM(I)=0.
  12  EATER(I)= P(61)
  14  ICANF=P(15)/DTAU
      ICANF=ICANF+1
      WRITE(6,15)  ICANF
  15  FORMAT(" FIRST COHORT WHICH MAY CANNIBALIZE IS",I4)
  25  FORMAT ( " HOWEVER, AVAILABILITY TO CANNIBALISM EQUALS ZERO.")
      IF (P(5).LE.0.) WRITE (6,25)
      IF (.NOT.DOBEV) GO TO 30
      P(97)=0.
      P(74)=0.
  30  CALL WPARS
C- IF LAYING=TRUE, FCF AND FCM ARE NEEDED TO DETERMINE STATE OF SYSTEM;
C- IT IS ALSO NECESSARY TO CALCULATE OR READ IN: EATER, ICANE.
      IF (LAYING .AND. FCF(ICANE).LT.0. .AND. .NOT.DOBEV)
     & CALL MSTOP( "NO FECUNDITIES,EATER,ICANE",26)
      IF(P(103).GT.P(94).OR.P(94).GT.P(95).OR.P(95).GT.1.) CALL MSTOP(
     -"ERR;P(103),P(94),P(95)",22)
      RETURN
 2990 WRITE(6,2991)
C* EVENTS 2 THROUGH 6 ARE REQUIRED.
 2991 FORMAT (" ERROR - MISSING EVENT(S)")
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 3000 WRITE (6,3100) CYCLE,CYOFF,DTAU,US,UC,EGGDUR,PREDUR,NOUPDA,IPAIR
 3100 FORMAT (" BAD CYCLE VALUES.  CYCLE="E22.15", CYOFF="G13.5 ", DTAU="
     & E22.15/ " AMOD(CYCLE,DTAU)="E22.15 ", SUM(TEV,1,NEV)="E22.15
     &", EGGDUR="G13.5 ", PREDUR="G13.5/" NOUPDA="L3", IPAIR="I19)
      CALL MSTOP( "BAD CYCLE VALUES",16)
      END


      SUBROUTINE INIT
C  DETERMINE WHERE WE ARE IN THE CYCLE OF EVENTS (IE, DETERMINE NEXT
C  DISCRETE TIME EVENT TO BE PERFORMED).
      LOGICAL UFL
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      JEV=NEV
      ISEQ=0
      UEV=0.
      CT = AMOD(TF + CYCLE - CYOFF , CYCLE)
C  SET DEFAULT VALUE  FOR LAYING.
      LAYING=.FALSE.
C- CHECK IF COHORT 1 IS BREEDING (ASSUME COHORT 1 USED TO EAT IF IT IS
C- NOW OLD ENOUGH TO BREED):
      UFL=FCF(1)+FCM(1) .LE. 0.
C  WE ASSUME IF THE TIME FALLS EXACTLY ON A CERTAIN EVENT TIME THAT THE
C  EVENT HAS ALREADY BEEN PERFORMED.
 15   IF (CT.LT.UEV) GO TO 20
      ISEQ=ISEQ + 1
      UEV = UEV + TEV(ISEQ)
      IF (ISEQ.GT.JEV) GO TO 90
      GO TO 15
 20   NXTEV(ISEQ) = UEV-CT+TF
      IF (JEV.LE.1) GO TO 50
      DO 25 I=2,JEV
      GO TO ( 25,102,103,104,105,106,107,108, 25, 25 , 25) ,
     &IEV( MOD( I+ISEQ-2 , JEV) + 1 )
 102  LAYING=.TRUE.
      GO TO 25
 103  RIPEN=.TRUE.
      GO TO 25
 104  IF (UFL) EATER(1)=0.
      RIPEN=.FALSE.
      GO TO 25
 105  LAYING=.FALSE.
      GO TO 25
 106  IF (UFL) EATER(1)=P(61)
```

```
      GO TO 25
 107  FISHIN=.TRUE.
      GO TO 25
 108  FISHIN=.FALSE.
 25   CONTINUE
      IF (ISEQ-JEV) 42,50,90
 42   JSEQP = ISEQ + 1
      DO 45 I=JSEQP,JEV
      NXTEV(I) = NXTEV(I-1) + TEV(I)
 45   CONTINUE
 50   NXTEV(JEV+1) = NXTEV(JEV) + TEV(1)
C  TSTP IS THE NUMBER OF TIME CYCLES FOR WHICH INTERMEDIATE POINTS HAVE
C  BEEN CALCULATED.
      TSTP=1
      RETURN
 90   CALL MSTOP ("ERROR SETTING CYCLE STEPS IN INIT",33)
      END


      SUBROUTINE SRT (MEV,NEV,TEV,IEV)
C  SORT THE ELEMENTS MEV THROUGH NEV OF ARRAY TEV INTO ASCENDING ORDER.
C  ARRAY IEV IS REARRANGED THE SAME WAY TEV IS REARRANGED.
C  WHEN CHECKING THIS SUBROUTINE, BE SURE THE LEAST ELEMENT OF TEV
C  STARTS OUT INTERCHANGED WITH SOME OTHER ELEMENT.
      DIMENSION TEV(NEV) , IEV(NEV)
      IONE = MEV
      IEND = NEV
      INEXT = IONE+ 1
 9    IF (INEXT.GT.IEND) RETURN
      I = INEXT
 10   IF (TEV(I-1).GT.TEV(I)) GO TO 29
      IF (I.GE.IEND) RETURN
      I = I+1
      GO TO 10
 29   INEXT = I+ 1
C  IF TEV STARTS OUT HIGHLY DISORDERED, A BINARY SEARCH IS BETTER BELOW:
C- HOWEVER FOR POL, IF 2 ELEMENTS OF TEV ARE EQUAL, PRESERVE THEIR ORDER.
 30   UA=TEV(I)
      JA=IEV(I)
      ISUB = I-1
      IEV(I)=IEV(ISUB)
      TEV(I) = TEV(ISUB)
      TEV(ISUB) = UA
      IEV(ISUB) = JA
      I=ISUB
C THE TWO BELOW IF STATEMENTS MIGHT BE NECESSARY IF MEV EQUALS 1:
      IF (I.LE.IONE) GO TO 9
      IF (TEV(I-1).LE.TEV(I)) GO TO 9
      GO TO 30
      END


      SUBROUTINE SUB
C  ON INPUT, TEV CONTAINS THE TIME CYCLE EVENTS OCCUR, IN YEARS AFTER
C  TIME 0 (0000 HOURS ON JAN. 1).
C  ON EXIT FROM SUB, TEV(I) IS THE TIME BETWEEN EVENT I-1 AND EVENT I,
C  EXCEPT TEV(1) IS THE TIME BETWEEN THE LAST EVENT AND THE FIRST EVENT
C  OF A NEW CYCLE.
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
```

```
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
C  CHECK THAT TEV IS ARRANGED IN ASCENDING ORDER:
      CALL SRT (1, NEV, TEV, IEV)
C  CYOFF IS SET TO EQUAL THE LARGEST VALUE IN TEV:
      CYOFF = TEV(NEV)
      JN= NEV - 1
      USUM=0.
      DO 20 J=1, JN
      I=NEV+1-J
      TEV(I) = TEV(I) - TEV(I-1)
      USUM=USUM+TEV(I)
 20   CONTINUE
C* THIS ENSURES THAT THE ELEMENTS OF TEV SUM TO CYCLE DESPITE TRUNCATION
      TEV(1)=CYCLE-USUM
      TEV(1)=TEV(1)+(CYCLE-(USUM+TEV(1)))
C* CHECK WHETHER ROUNDING ERRORS HAVE CAUSED A NEGATIVE TEV(1)
      IF (TEV(1).LT.0.) CALL MSTOP( "NEGATIVE TEV(1)", 15)
      RETURN
      END


      SUBROUTINE PHYMOD
C  CALCULATE OR CHANGE UNITS OF INPUT PARAMETERS FOR PRIMARY PRODUCTION
C  (PHYTOPLANKTON) SUBMODEL.  PHYMOD IS CALLED FROM INPUTR.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAG, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17,20), WL(20), YT, CT, PREDUR, HOMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
C  CHANGE FROM DAYS TO YEARS.
      DO 10 I=21, 26
      P(I) = P(I)/365.
 10   CONTINUE
C- ADJUST TOTAL AMOUNTS OR RATES OF INPUT
      DO 15 I=27, 31
 15   P(I) = P(11)*P(I)
C  SET SEA ICE SEASON LENGTH.
      P(32) = P(22)-P(21)
C SET SPRING LENGTH.
      P(33) = P(24)-P(23)
C  SET SUMMER LENGTH.
      P(34) = P(25)-P(24)
C  SET FALL LENGTH.
      P(35) = P(26)-P(25)
C  CALCULATE PRODUCTION BY SEA-ICE ALGAE
      P(88)=P(27)-P(31)*(P(23)-P(21))
C  SUMMER PRODUCTION PARAMETERS.
      P(37) = P(29) - P(31)*P(34)
C  CALCULATE SUMMER CONSTANT PRODUCTION RATE=UA (IN ADDITION TO
C  YEAR-AROUND CONSTANT PRODUCTION RATE, P(31)).
      UA = P(37)/P(34)
```

```
C  SPRING PRODUCTION PARAMETERS.
C  CALCULATE AMOUNT=UB ATTRIBUTED TO INCREASE FROM WINTER TO SUMMER
C  (ADDED IN WITH FUNCTION FLTTOP).
      UB = .5*P(33)*UA
      P(36) = P(28) - UB - P(31)*P(33)
C  FALL PRODUCTION PARAMETERS.
C  CALCULATE AMOUNT=UC ADDED IN WITH FLTTOP DURING THE FALL
      UC = .5*P(35)*UA
      P(38) = P(30) - UC - P(31)*P(35)
      RETURN
      END


      FUNCTION RLNGTH (UA)
C RLNGTH CALCULATES THE VON BERTALANFFY LENGTH OF AN ANIMAL OF AGE UA.
C HOWEVER, IF UA IS   .LT.    P(12), LENGTH IS LINEAR.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
C .LT.  IS USED BELOW BECAUSE OF THE WAY D9 IS  SET IN PARMOD.
      IF (UA.LT.P(12)) GO TO 20
      RLNGTH=D7*(1.-EXP(KAY*(D4-UA)))
      RETURN
 20   RLNGTH=D9*UA+P(14)
      RETURN
      END


      FUNCTION WVB(UD)
C CALCULATES THE WEIGHT OF AN ANIMAL OF AGE UA.
C IF UA IS   .LT.    P(12), GROWTH IS LINEAR. OTHERWISE, GROWTH IS
C ACCORDING TO THE VON BERTALANFFY CURVE.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
      UA=UD
C .LT.  IS USED BELOW BECAUSE OF THE WAY D6 IS SET IN PARMOD.
      IF(UA.LT.P(12)) GO TO 20
      WVB=WOO*(1.-EXP(KAY*(D4-UA)))**D2
      RETURN
 20   WVB=D6*UA+P(13)
      RETURN
      END


      SUBROUTINE SIM
C* STARTS THE SIMULATION, PERFORMS REGULARLY SCHEDULED PRINT TIMES,
C* TESTS FOR THE END OF THE SIMULATION, AND STOPS THE SIMULATION.
CDC   OVERLAY(P,2,0)
CDC   PROGRAM SIM
```

```
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      T2=TF
      TT=T2
      TPT=AMOD(TPOFF,1.)-AMOD(TF,1.)
      IF (TPT.LT.0.) TPT=TPT+1.
      IF (TPT.EQ.0.)TPT=TP
      CALL ILLUS(.TRUE.)
      IF (.NOT.FISHIN) YLD=0.
C   START SIMULATING
 1    T=T2
      IF (T2+TDMIN .GT. TL) GO TO 10
      T2=AMIN1(TL,T+TPT)
      TPT=TP
      CALL ANALY(T,T2)
      CALL ILLUS(T2.GE.STPRNT)
      GO TO 1
C- FILES MAY NEED TO BE CLOSED IN SUBROUTINES SIM OR CALC.
 10   IF (T.GE.STPNCH) CLOSE(7,DISP=CRUNCH)
      IF (DD) CLOSE(4,DISP=CRUNCH)
      CLOSE(9)
      RETURN
      END


      SUBROUTINE ANALY(T1,T2)
C* PERFORMS DISCRETE TIME EVENTS
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
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```
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY, IER, LIER, IERTOT, RQMAX, SHER(5,7), TDMIN, TDIMIN,
     -TDMAX, KE, NZ, NQ(67), VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAQ, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17,20), WL(20), YT, CT, PREDUR, HDMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, COMAX, ASTOP, DD,
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C  IEV(ISEQ) IS THE IDENTIFIER OF THE EVENT WE ARE PERFORMING OR ABOUT
C  TO PERFORM.
C----- IEV CONTAINS EVENT IDENTIFIERS AS SHOWN -----:
C  1  PRINT TIMES(EXCEPT REGULARLY SCHEDULED ONES CALCULATED WITH TPT, TP
C  2  POLLOCK PREPARE TO BREED (EATER REDUCED?)
C  3  POLLOCK BREED (SPAWN)
C  4  COHORT UPDATE TIME (POLLOCK EGGS HATCH)
C  5  POLLOCK EGGLAYERS CEASE BREEDING PERIOD (EATER INCREASED?)
C  6  NEWLY HATCHED POLLOCK START EATING.
C  7  FISHING STARTS.
C  8  FISHING ENDS.
C  9  ?
C  10  ?
C  11  JAN. 1 - TIME 0 IS ALWAYS 0000 HOURS ON JAN. 1 OF SOME YEAR.
C  IF THE ABOVE ARE CHANGED, CHANGE SETTING EGGDUR, PREDUR IN PARMOD.
C  AN EVENT MAY OCCUR 0, 1, OR MORE TIMES IN A CYCLE.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      T=T1
      JEV=NEV
      GO TO 12
C     SET UP TIME POINTS
 11   NXTEV(1) = NXTEV(JEV+1)
      ISEQ=1
      DO 7 I=2,JEV
      NXTEV(I) = NXTEV(I-1) + TEV(I)
 7    CONTINUE
      NXTEV(JEV+1) = NXTEV(JEV) + TEV(1)
      TSTP = TSTP+1
C  INTEGRATE TO THE NEXT TIME POINT.
 12   UEV = AMIN1(T2,NXTEV(ISEQ))
C  IF (UEV-T.GT.0 .AND. UEV-T.LT.TDMIN) THEN ERRORS WOULD OCCUR IF AGE
C WERE CALCULATED IN CALC, BUT IF TDMIN WERE SMALL, THEY WOULD BE MINOR.
      IF (UEV-T.GE.TDMIN) CALL CALC(T,UEV)
      T=UEV
      TT=T
C  IF AN EVENT AND A REGULARLY SCHEDULED PRINT TIME COINCIDE, THE EVENT
C  HAPPENS FIRST. THIS INSURES ALL EVENTS OCCUR BEFORE WE STOP THE
C  SIMULATION.
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      IF (T2-T.LT.TDMIN .AND.  T.LT.NXTEV(ISEQ)) RETURN
      I=IEV(ISEQ)
      ISEQ = ISEQ+1
      GO TO  (13,15,14,19,23,26,17,21,12,12,12),I
C  IF A PRINT EVENT AND A REGULARLY SCHEDULED PRINT TIME COINCIDE AND
C OCCUR CONSECUTIVELY, THIS TEST INSURES ONLY THE REGULAR ONE IS DONE:
 13   IF(T2-T.GE.TDMIN.OR.T.GE.NXTEV(ISEQ))CALL ILLUS(T.GE.STPRNT)
      IF (JEV-ISEQ) 11,12,12
 14   CALL LAYEGG
      IF (JEV-ISEQ) 11,12,12
C  BREEDERS STOP EATING
 15   CALL PRELAY
      IF (JEV-ISEQ) 11,12,12
C  BREEDERS FINISH LAYING
 23   LAYING=.FALSE.
      IF (NC.LT.ICANE) GO TO 34
      DO 33 II=ICANE,NC
      FCF(II)=0.
      FCM(II)=0.
 33   EATER(II) = P(61)
 34   IF (JEV-ISEQ) 11,12,12
C* NEWLY HATCHED POLLOCK START EATING.
 26   EATER(1)=P(61)
C* GCN(1) IS RESET IN COHUP,CALC,ANALY(EAT START TIME)
      GCN(1)=0.
C- IF CHANGED BELOW, CHANGE BOTH PRINTR, AND ANALY.
      UT=TT-TCUM
      TCUM=TT
      IF(UT.GT.0..AND.TT.GE.STPRNT)WRITE(6,335)TT,UT,VCUM,(VCUM(1)+
     &VCUM(2))/UT,ZBS
 335  FORMAT(/" ;;;;;;;; TIME=",F9.4,",  CUM.DUR=",F9.4,",  CUM.COPE=",
     *E13.8,",  CUM.EUPH=",E13.8,",  AV.TOT.ZOO.=",E13.8/" MIN.TOT.ZOO=",
     *E13.8)
      ZBS=COPE+EUPH
      VCUM(1)=0.
      VCUM(2)=0.
      NOCUM=(TT.LT.STPRNT-DTAU-TDMIN) .AND.  (.NOT.DD)
      IF (JEV-ISEQ) 11,12,12
C  FISHING STARTS
 17   CALL EFFORT
      IF (JEV-ISEQ) 11,12,12
C  FISHING STOPS
 21   FISHIN = .FALSE.
      IF (TT.GE.STPRNT) WRITE (6,31) YLD,T-FSTART,T
 31   FORMAT (/" >>>>>>>>>> YIELD(GRAMS CATCH)="E15.10
     &", LENGTH OF SEASON(IN YEARS)="F9.4",  TIME="F9.4" <<<<<<<<<<")
      IF (JEV-ISEQ) 11,12,12
C- CHECK FOR STATIONARY CONDITIONS:
 19   CALL AGESTA(T2)
C  ON INPUT, TEV SHOULD BE ARRANGED SO EGGLAYING ALWAYS TAKES PLACE
C  BEFORE ANY COHORT UPDATE - EVEN IF  THEY ARE "SIMULTANEOUS."
C     UPDATE COHORTS
      CALL COHUP
C     RETURN FOR INTEGRATION IF NECESSARY
      IF (JEV-ISEQ) 11,12,12
      END


      SUBROUTINE ILLUS(ULOG)
C* SUPERVISES PRINTING OUT OF TABLES AND GRAPHS.
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      LOGICAL ULOG
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      NTT=SUM(N,1,NC)
      IF (.NOT.SHOWB) GO TO 505
      BTT= 0.
      DO 480 I=1,NC
      B(I) = N(I)*W(I)
      BTT = BTT+B(I)
 480  CONTINUE
      B313=SUM(B,3,MIN0(13,NC))
 505  IF (DD) WRITE(4,510)TT,NC,ETT,E,PHY,COPE,EUPH,FSTART,YLD,TCUM,
     -VCUM,(N(I),W(I),L(I),I=1,NC)
C-    VCUM HAS 2 ELEMENTS.
C- THE FORMATS LABELLED 510 IN INPUTR, ILLUS SHOULD NOT CONFLICT:
 510  FORMAT(3X,F11.4,I3,5E11.6/(7E11.6))
      IF(ULOG) CALL PRINTR
      IF (DOGRPH) CALL SHOW
      RETURN
      END


      SUBROUTINE PRINTR
C* PRINTS OUT TABLES
      DIMENSION IND(17)
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MERA"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),NDOT(20),WDOT(20),LDOT(20),VDOT(7)
      REAL NDOT,LDOT
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),QCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
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```
      COMMON /CONTRL/ NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, COMAX, ASTOP, DD,
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
$INCLUDE "L/I/NAME"
      NAMELIST/ISVN/MT, RC, FD, ICANDQ, ICANFQ, IDOF, IEXIST, NOCOH, ZM, FCF, FCM,
     -EATER, LAYING, RIPEN, FDU, HLCAND, YT, CT, FSTART, FISHIN, SM, WL, CN, ICANAQ
      NAMELIST/PARP/P
      NAMELIST/PARS/KAY, D2, D4, D7, D8, NMIN, PLENTY, Q2, ZLNG, ZW, EF, M, F,
     -FISHIN, FSTART, ICANE, EGGDUR, WOO, HOMAX, PREDUR, AOFF, EATER, FCF, FCM
      NAMELIST/CTRL/NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, TDL, IERTOT, RQMAX,
     -COMAX, CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV, TEV, NXTEV, NGR, IGR, DOGRPH, NOCUM
      NAMELIST/CTRLRD/TF, TL, STPRNT, STPNCH, DD, PCHEND, DOBEV, RDWGHT, TP,
     -TPOFF, DOGRPH, SHOWB, SHOWD, DBUG, TD, TDMIN, TDMAX, ACCRCY, DTAU, NC, COMAX,
     -NVON
      DATA IND /1,2,3 ,14*0/
C  ETT SHOWS THE NUMBER OF EGGS LAID.
C TT IS THE CURRENT TIME, AND IS UPDATED IN SIM, ANALY, AND MERSON.
      T=TT
      IF (T.GE.STPNCH)
     &WRITE (7,330) T,NC,E,PHY,COPE,EUPH,YLD,(N(I), W(I),L(I),I=1,NC)
 330  FORMAT (3X,F9.4,I3,5E13.8/3(2E10.5,F6.3),7(/3(2E10.5,F6.2)))
C* FORMAT 251(INPUTR) AND FORMAT 330(PRINTR) SHOULD CORRESPOND.
      WRITE (6,300) T,NC,ICANE,ICANAQ,ICAND,NTT,ETT,E,PHY,COPE,EUPH,
     &YLD,TD,TDIMIN,(I,N(I),W(I),L(I) , I=1,NC)
 300  FORMAT(/1X"?????????? TIME="F9.4",  NC=",I3,",ICANE=",I3,",ICANAQ="
     -,I3,",ICAND=",I3,",  NTT=",E13.8,",ETT=",E13.8,",E=",E13.8,
     -/1X," PHY=",E13.8,",COPE=",E13.8,",EUPH=",E13.8,",YLD=",E13.8,
     -",  TD=",E19.14,",TDIMIN=",E19.14,","/1X," I,N(I),W(I),L(I)="
     & /8(1X,4(I2,E12.5,F11.5,F7.3,1H")/))
C- IF CHANGED BELOW, CHANGE BOTH PRINTR, AND ANALY.
      UT=TT-TCUM
      IF(UT.GT.0.)WRITE(6,335)UT,VCUM,(VCUM(1)+VCUM(2))/UT,ZBS
 335  FORMAT(" ;;;;;;;; CUM.DUR=",F9.4,",  CUM.COPE=",E13.8,",  CUM.EUPH="
     *,E13.8,",  AV.TOT.ZOO.=",E13.8,",  MIN.TOT.ZOO=",E13.8)
      TDIMIN=TD
      IF (SHOWB) WRITE (6,490) BTT,B313,(I,B(I) , I=1,NC)
 490  FORMAT(" BIOMASS(TOTAL POLLOCK)="E13.8 ",  BIOMASS COHORTS 3-13="
     &,E13.8,",  INDIVIDUAL COHORT BIOMASSES=",3(/7(" ("I2","E13.8")")))
C  CHECK THAT DERIVATIVES, FOOD FRACTIONS, ETC., HAVE BEEN CALCULATED.
      IF (KE.LT.1) GO TO 685
C- IF THE TIME SPACING BETWEEN EVALUATION OF DERIVATIVES IS CHANGED IN
C- NUMERICAL INTEGRATION, THEN ALSO CHANGE THE CALCULATION OF UTLDER:
      UTLDER=TT-.5*TDL
      IF (.NOT.SHOWD) GO TO 599
C NOTE THE BELOW WERE CALCULATED THE SAME TIME AS DERIVATIVES - NOT NOW.
C CONFUSION CAN RESULT - ESPECIALLY IMMEDIATELY AFTER A COHORT UPDATE.
      WRITE (6,509) UTLDER
 509  FORMAT(" FOOD FRACTION FOR COHORT (COH) FROM SOURCES: 1-3 PHYTOPLA
     -NKTON,COPEPODS,EUPHAUSIIDS; 4-12 POLLOCK.  FROM TIME=",E19.14)
      JDQP3 = ICANDQ+3
      IF (NOCOH) GO TO 516
      DO 515 KI=1,NZ
      I=NQ(KI)
      IF (RC(I).GT.0.) GO TO 512
      WRITE (6,511) I,GCN(I),CN(I),FD(I),SM(I),MT(I)
```

```
 511  FORMAT (" COH"I3"-NO FOOD"T80"GCN="F6.3",CN="F6.3",FD="G9.3
     -",SM="F7.3",MT="F6.3)
      GO TO 515
C RECALL ONLY COHORT 1 MAY EAT PHYTOPLANKTON.  IDOF (SET IN ISV) POINTS
C TO THE FIRST CANNIBALIZING COHORT.
 512  JJ=3
      JI=MINO(I,2)
      IF (KI.LT.IDOF) GO TO 513
      JJ=JDQP3
      DO 520 J=4,JJ
 520  IND(J) = NQ(J-3)+3
 513  WRITE(6,514)I,RC(I),GCN(I),CN(I),FD(I),SM(I),MT(I),(IND(J),
     *D(IND(J),I)/FD(I),J=JI,JJ)
 514  FORMAT(" COH="I2,1H,,T67"RC="G9.3",GCN="F6.3",CN="F6.3",FD="G9.3
     -",SM="F7.3",MT="F6.3,T9,8(I1,1H=,F4.3,1H,)/T9,15(I2,1H=,F4.3,1H,))
      IF (DBUG)WRITE (6,518) (IND(J   ),  D(IND(J),I),  J=JI,JJ)
 518  FORMAT (1X,  11(I2,1H=,E8.2,1H,))
 515  CONTINUE
 516  PRINT /,"ZM.  CP=",ZM(1),"EP=",ZM(2),"PP=",ZM(3),
     * "EC=",ZM(4),"PC=",ZM(5),"PE=",ZM(6)
 599  IF (.NOT.DBUG) RETURN
      IF (NOCOH) GO TO 670
      WRITE (6,600)KD,NZ,KE,IEXIST,UTLDER,(NQ(I),NDOT(NQ(I)),WDOT(NQ(I))
     - ,LDOT(NQ(I)) ,  I=1,NZ)
 600  FORMAT(" DERIVS POLLOCK, KD="I3", NZ="I3", KE="I3", IEXIST="I3,
     - ",  FROM TIME=",E19.14,  7(/3(I3,3G12.5,1H,)))
 670  JZ3P=3*NZ+1
      IF (JZ3P.GT.KE) GO TO 675
      WRITE (6,601) UTLDER ,  (I,NQ(I),  VDOT(NQ(I)-3*KD) ,  I=JZ3P,KE)
 601  FORMAT (" OTHER DERIVS FROM TIME=",E19.14,  (/6(2I3,G12.5,1H,)))
 675  WRITE (6,CTRL)
      WRITE (6,ISVN)
      WRITE (6,/) "B=",B
       CALL WPARS
       WRITE(6,PARS)
      RETURN
 685  IF (DBUG) GO TO 675
      RETURN
      END


      SUBROUTINE SHOW
C* MAKES GRAPHS
C THE DIMENSION OF LC SHOULD BE .GE. THE DIMENSION OF IGR.
C* LC IS DIMENSIONED IN BOTH SHOW AND LCSET.  THEY SHOULD AGREE.
      DIMENSION LC(32)
$INCLUDE "L/I/STATB"
      COMMON /STATE/ B(93)
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
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     -TDMAX, KE, NZ, NQ(67), VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, COMAX, ASTOP, DD,
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
      JC=0
C  JC HAS 1 ADDED TO IT EACH TIME SUBROUTINE LCSET IS CALLED.
C  GRAPH TOTAL NUMBER OF POLLOCK MINUS FIRST COHORT.
      CALL LCSET (B(70)-B(1), JC, LC, IFILE(1))
C* GRAPH TOTAL NUMBER OF POLLOCK LARGE ENOUGH IN SIZE FOR SOME TO BREED.
      CALL LCSET(B(70) - SUM(B, 1, ICANE-1) ,  JC, LC, IFILE(2))
      DO 5 I=3, NGR
      CALL LCSET(B(IGR(I)), JC, LC, IFILE(I))
 5    CONTINUE
      DO 15 J=1, NFILE
      JFIL=10+J
      IF (IGL(J).LT.66) GO TO 8
      JJ=IHD(J)
      JDEC=IHDEC(J)
      WRITE (JFIL, 7)(IFIX(SCALM(J)*(I-1)+SCALC(J)-2.), I-1, I=1, JJ, JDEC)
 7    FORMAT (1H1, 32(T*, I4))
      IGL(J)=1
 8    WRITE (JFIL, 10) TT, LIER
 10   FORMAT (1H , F9.4, A1 )
      IGL(J)=IGL(J)+1
 15   CONTINUE
      CALL GRAPHR (LC, 12, 132, 1,  JC, IFILE)
      LIER=1H:
      RETURN
      END


      SUBROUTINE GRAPHR (LC, LF, LU, JF, JL, IFILE)
C* GRAPHS VALUES
      DIMENSION IA(26), IFILE(JL), LC(JL)
C  IA IS A SOURCE STRING OF CHARACTERS.
      DATA IA/1HA, 1HB, 1HC, 1HD, 1HE, 1HF, 1HG, 1HH, 1HI, 1HJ, 1HK, 1HL, 1HM, 1HN,
     * 1HO, 1HP, 1HQ, 1HR, 1HS, 1HT, 1HU, 1HV, 1HW, 1HX, 1HY, 1HZ/
C  LC IS A MATRIX OF VALUES (INTEGERS) TO BE GRAPHED.
C  JF IS THE FIRST ELEMENT OF MATRIX LC TO BE GRAPHED,  JL IS THE LAST.
C  LF AND LU ARE THE BOUNDS FOR THE LC.
C  LF MUST BE GREATER THAN OR EQUAL TO 1,  LU LESS THAN OR EQUAL TO 136.
C* LU MUST BE .LE.  132 ON THE NWAFC BURROUGHS B6800.
      DO 30 I=JF, JL, 1
      IF (LC(I).LT.LF.OR.LC(I).GT.LU) GO TO 30
      LD=LC(I)-1
C  GRAPH THE VALUE:
      WRITE (IFILE(I), 11) LD, IA(MOD(I-1, 26)+1)
 11   FORMAT (1H+, *X, A1)
 30   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE LCSET (X,JC,LC,JFIL)
C* TRANSFORMS VALUES TO PREPARE FOR GRAPHING
C* LC IS DIMENSIONED IN BOTH SHOW AND LCSET.  THEY SHOULD AGREE.
      DIMENSION LC(32)
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      JC=JC+1
      UX=X
      JCAS=JFIL-10
C  CHECK FOR INDEFINITE OR OUT OF RANGE VALUES:
CDC   IF (LEGVAR(UX).NE.0) GO TO 10
      IF(ITRAN(JCAS)-2) 100,200,300
 100  LC(JC)=SCALM(JCAS)*UX+SCALC(JCAS)
      RETURN
C- IF LF IN GRAPHR IS .LE.11, LOW VALUES ARE GRAPHED IN COL 11:
 200  LC(JC)=11
      IF (UX.LT.NMIN) RETURN
C WE WISH ROUNDED SCALED VALUES
      LC(JC)=SCALM(JCAS)*ALOG10(UX)+SCALC(JCAS)
      RETURN
 300  LC(JC)=SCALM(JCAS)*EXP(UX)+SCALC(JCAS)
      RETURN
CDC10   LC(JC) = 4096
C THIS CAUSES NOTHING TO BE GRAPHED BY GRAPHR,UNLESS PAGE WIDTH.GT.4096
CDC   RETURN
      END


      FUNCTION SUM(B,JI,JJ)
C* SUMS THE ELEMENTS OF AN ARRAY
      DIMENSION B(JJ)
      SUM=0.
      J=JJ
      IF (J.LT.JI) RETURN
      US=0.
      DO 10 I=JI,J
 10   US=US+B(I)
      SUM=US
      RETURN
      END


      SUBROUTINE PRELAY
C* ADULT POLLOCK PREPARE TO BREED.  PRELAY IS CALLED FROM ANALY.
$INCLUDE "L/I/ISV"
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      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAQ, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17,20), WL(20), YT, CT, PREDUR, HOMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC, TD, TT, DTAU, TSTP, DOBEV, TP, TF, TL, COMAX, ASTOP, DD,
     -DBUG, TDL, RDWGHT, SHOWB, SHOWD, PCHEND, STPRNT, STPNCH, TPOFF, NVON, NOCUM
      COMMON/GRAPH/ DOGRPH, NGR, IGR(32), IFILE(32), NFILE, SCALM(7), ITRAN(7)
     -, SCALC(7), IGL(7), IHD(7), IHDEC(7)
      INTEGER TSTP, COMAX
      LOGICAL DBUG, RDWGHT, SHOWB, SHOWD, DOGRPH, PCHEND, DOBEV, NOCUM, ASTOP, DD
      COMMON/EVENT/CYCLE, CYOFF, AOFF, ISEQ, NEV, IEV(32), TEV(32), NXTEV(33)
      REAL NXTEV
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20), W(20), L(20), PHY, COPE, EUPH, YLD, E, VCUM(2), KD, ETT,
     &NTT, BTT, B(20), B313, TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N, W, L, B, SM, MT,  ETC.
      REAL N, NTT, L
C IF COMMON BLOCK /STATE/ IS CHANGED,  COMDECKS L/I/STATE,  L/I/STATA,
C L/I/STATB,  L/I/STATV,  AND USE OF B IN AGESTA,  SHOW MAY NEED CHANGING.
      IF (DOBEV) RETURN
      LAYING=.TRUE.
      ICANE=COMAX+1
C  FIND PROPORTION OF FISH NOT REFRAINING FROM EATING DUE TO BREEDING.
      DO 10 I=1, NC
      FCF(I)=0.
      FCM(I)=0.
      IF (N(I).LT.NMIN) GO TO 10
C DURING COHORT UPDATES IN COHUP,  SHIFT EATER, FCF, FCM.
      CALL FECUND(L(I), FCM(I), FCF(I))
      UF=FCM(I)+FCF(I)
      EATER(I)=P(61)-P(62)*UF
      IF (UF.GT.0.) ICANE = MINO(I, ICANE)
 10   CONTINUE
      IF (TT.LT.STPRNT) RETURN
      WRITE(6,15)TT, NC, ICANE, (EATER(I), I=1, NC)
      WRITE(6,16)(FCF(I), I=1, NC)
      WRITE(6,17)(FCM(I), I=1, NC)
 15   FORMAT(/" <<<<<<<<TIME=", F9.4, ",  NC=", I3, ",  ICANE=", I3/
     -" EATER=", 20F6.3)
 16   FORMAT(3X, "FCF=", 20F6.3)
 17   FORMAT(3X, "FCM=", 20F6.3)
      RETURN
      END


      SUBROUTINE FECUND(UL, UM, UF)
C- CALCULATES THE FRACTIONS OF THE MALE AND FEMALE POLLOCK POPULATIONS
C- WHICH ARE MATURE ENOUGH TO BREED.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAQ, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17,20), WL(20), YT, CT, PREDUR, HOMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
```

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C- MALES
      UM=EXP(P(107)*EXP(P(108)*UL))
      IF (UM.LT.P(86)) UM=0.
      IF (UM.GT.P(87)) UM=1.
      UM=P(120)*UM
C- FEMALES
      UF=EXP(P(109)*EXP(P(110)*UL))
      IF (UF.LT.P(86)) UF=0.
      IF (UF.GT.P(87)) UF=1.
      UF=P(20)*UF
      RETURN
      END


      SUBROUTINE LAYEGG
C- ADULT POLLOCK SPAWN.  LAYEGG IS CALLED FROM ANALY.
      LOGICAL ULOG
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT,  ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      ETT=0.
      IF (DOBEV) GO TO 19
C- ICANE IS CALCULATED IN PRELAY
      IF (NC.GE.ICANE) GO TO 3
      E=P(74)
      RIPEN=.TRUE.
      RETURN
 3    ULOG=TT.GE.STPRNT
      IF (ULOG) WRITE (6,5) TT
 5    FORMAT(/" !!!!!!!!! EGGS OF FEMALES.  TIME=" F9.4,5X,8("!!!!!!!!!")
     &/ " COHORT",2X,"WEIGHT OF IND.",2X,"PO. NO. OF EGGS",2X,
     & "TOTAL EGGS COHORT",4X,"AV.NEW WGHT",3X,"(OLD+NEW)/2",3X,
     &"WL WEIGHT",4X,"FCF",3X,"FCM",4X,"POP.")
      UW=0.
      UG=0.
      IF(ICANE.LE.NVON.AND.ULOG)PRINT/,"WEIGHT NOT REDUCED FOR COHORTS",
     *NVON," OR LESS."
      DO 10 I=ICANE,NC
      UF=FCF(I)+FCM(I)
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      IF (N(I).LT.NMIN.OR. UF.LE.O.) GO TO 10
C- EXPECTED WEIGHT
C- IF EXPONENT 3 IS CHANGED BELOW, THEN CHANGE THE DEFINITION AND
C- CALCULATION OF P(4), P(70), AND THEIR USE IN SUBROUTINES LAYEGG, ISV.
      UWL=P(70)*L(I)**3
      IF (L(I).LT.P(4)) UWL=P(80)*L(I)**P(63)
C- NUMBER OF EGGS
      UC = W(I)*P(6)
C- WEIGHT LOSS DUE TO EGGS OR MILT
      UV=UC*P(10)
C- TOTAL EGGS COHORT
      UE=UC*N(I)*FCF(I)
C- AVERAGE NEW WEIGHT ASSUMING THE SAME WEIGHT LOSS FOR MALES AND
C- FEMALES. SPAWNING MORTALITIES RESULTING FROM AVERAGING MIGHT BE
C- DIFFERENT FROM THOSE CALCULATED IN A MORE COMPLEX MODEL.
      UN=W(I)-UV*UF
C  NO WEIGHT REDUCTION FOR GROWTH FORCED TO BE "VON BERTALANFFY".
      IF (I.LE.NVON) UN=W(I)
      IF(ULOG)WRITE(6,8)I,W(I),UC,UE,UN,(UN+W(I))/2.,UWL,FCF(I),FCM(I),
     -N(I)
 8    FORMAT (3X,I4,2X,E13.8,2X,E15.10,3X,E15.10,4X,3E14.8,2F6.3,E14.8)
      W(I) = UN
      UG=UG+UE*DTAU*I
      UW=UW+UE
 10   CONTINUE
      ETT=UW
C* AVERAGE GENERATION TIME CALCULATED WITH NO. OF EGGS LAID AS WEIGHTS,
C* WITH AGE OF PARENTS CALCULATED ASSUMING COHORT UPDATE OCCURS
C* WHEN EGGS HATCH:
      IF (UW.GT.O.) UG=UG/UW-EGGDUR
      GO TO 20
 19   ETT=P(64)
C CALCULATE EGG SURVIVAL ASSUMING INDEPENDENCE FROM OTHER STATE
C VARIABLES:
 20   E=ETT*EXP(-EF*EGGDUR)
      IF (E.LT.NMIN) E=P(74)
      RIPEN=.TRUE.
      IF (ULOG) WRITE (6,25) ETT,E,UG
 25   FORMAT (" ETT=",E13.8,", E=",E13.8,", AV. GENERATION TIME(WEIGHTED
     - BY NO. EGGS LAID)=",F9.5)
      RETURN
      END


      SUBROUTINE EFFORT
C- BEGIN THE "FISHING SEASON;" CALCULATE F.
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
```

```
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      NAMELIST /FISH/Q,XCATCH,XCPUE
      FISHIN = .TRUE.
      YLD = 0.
      FSTART=TT
C- IF AT END-OF-FILE, NO CHANGE IS MADE TO F:
      READ(5,FISH,END=99)
      XEFFRT=XCATCH/XCPUE
      UF=Q*XEFFRT
      DO 10 I=1,COMAX
 10   F(I)=UF
      WRITE(6,20)UF,TT,Q,XEFFRT,XCATCH,XCPUE,F
 20   FORMAT(/" ?????? NEW F=UF=",F14.11,",  TIME=",F9.4,",  Q=",
     -E11.6,",  XEFFRT=",E11.6,",  XCATCH=",E11.6,",  XCPUE=",E11.6/
     -" F=",20(F5.2,1H,))
 99   RETURN
      END


      SUBROUTINE AGESTA(T2)
C- TEST STATE VARIABLES FOR OCCURRENCE OF STATIONARY CONDITIONS.
C- AGESTA MUST BE CALLED BEFORE COHORT UPDATE, OTHERWISE CHANGE THE
C- USAGE OF ARRAY NQ.
C- IF DTAU.LT.1 OR IF THE MODEL IS MODIFIED TO INCLUDE STOCHASTIC
C- EFFECTS, THEN PERHAPS CHANGE SUBROUTINE AGESTA.
$INCLUDE "L/I/STATB"
      COMMON /STATE/ B(93)
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/AGEC"
      COMMON /AGEC/ IAKE,AC(67)
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      JE=KE
      I=1
C* PREPARE TO CHECK POLLOCK EGGS(CHANGE IF E IS INTEGRATED NUMERICALLY):
      JE=JE+1
      NQ(JE)=65
      IF (IAKE.NE.JE) GO TO 90
      U5=ACCRCY+ACCRCY
```

```
      DO 10 KI=1,JE
      I=NQ(KI)
      R=ABS(B(I))
C* THE BELOW CONSTANT(1E-5) IS USED IN AGESTA, MERSON, DETECT
      IF (R.GE.1E-5) GO TO 13
      R=U5
      GO TO 14
 13   R=R*U5
 14   IF (ABS(AC(I)-B(I)).GE.R) GO TO 90
 10   CONTINUE
      WRITE (6,32) U5,TT
 32   FORMAT(/" STATIONARY CONDITIONS. U5="G14.8",TIME="F9.4)
      IF (ASTOP) RETURN
C* PREPARE TO START PRINT OUTS
      STPRNT=TT
      NOCUM=.FALSE.
      UTL=AMIN1(AMOD(TL,1.)+AINT(TT)+DTAU+DTAU , TL)
      STPNCH=UTL+STPNCH-TL
      TL=UTL
      T2=AMIN1(T2,UTL)
      ASTOP=.TRUE.
      RETURN
 90   IF (ASTOP) WRITE(6,92) IAKE,JE,U5,I,AC(I),B(I),TT
 92   FORMAT(/" LOST STATIONARY CONDITIONS? IAKE="I2",JE="I2
     *",U5="G14.8",I="I2",AC(I)="E13.8",B(I)="E13.8",TIME="F9.4)
      DO 95 KI=1,JE
 95   AC(NQ(KI)) = B(NQ(KI))
      IAKE=JE
      RETURN
      END


      SUBROUTINE COHUP
C- COHUP UPDATES COHORTS, AND IS CALLED FROM ANALY.
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
```

```
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      NOCUM=(TT.LT.STPRNT-DTAU-TDMIN) .AND. (.NOT.DD)
      IF (NC.LT.1) GO TO 9
      IF (NC.LT.COMAX .AND. N(NC).GE.NMIN) NC = NC+1
      ICANE=ICANE+1
      IF (NC.EQ.1) GO TO 9
      DO 10 II=2,NC
      I=NC+2-II
      IM=I-1
      N(I)=N(IM)
      FCF(I)=FCF(IM)
      FCM(I)=FCM(IM)
      EATER(I)=EATER(IM)
      L(I)=L(IM)
      B(I)=B(IM)
      GCN(I)=0.
C- AFTER COHORT UPDATE, AGE(I) = (I-1)*DTAU + AMOD(TT +AOFF,DTAU)
      W(I)=W(IM)
      FDU(I)=P(17)
      IF (L(I).LT.P(111)) GO TO 10
      FDU(I)=P(114)
 10   CONTINUE
 3    IF (N(NC).GE.NMIN.OR.NC.LE.1) GO TO 9
      N(NC)=0.
      W(NC)=0.
      L(NC)=0.
      B(NC)=0.
C     NC MAY ALSO BE REDUCED IN CALC
      NC=NC-1
      GO TO 3
C     ADD NEW POLLOCK TO COHORT 1 (I.E. THE EGGS HATCH)
 9    N(1)=E
      W(1)=P(13)
      L(1)=P(14)
      EATER(1)=0.
      NC=MAX0(1,NC)
      E=0.
      RIPEN=.FALSE.
C* GCN(1) IS RESET IN COHUP,CALC,ANALY(EAT START TIME)
      GCN(1)=0.
      FCF(1)=-1.
      FCM(1)=-1.
C- IF E IS INTEGRATED NUMERICALLY, MAYBE CHANGE BELOW:
      PLENTY=.TRUE.
      IF (N(1).GT.0.) RETURN
      N(1)=0.
      W(1)=0.
      L(1)=0.
      B(1)=0.
      RETURN
      END

      SUBROUTINE CALC(T1,T2)
C- DECIDE WHICH QUANTITIES TO NUMERICALLY INTEGRATE
$INCLUDE "L/I/STATA"
      COMMON/STATE/N(20),W(20),L(20),V(4),E,VCUM(2),KD,ETT,NTT,BTT,B(20)
     *,B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
```

```
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      UMIN=NMIN
      ULMAX=0.
      JD=KD
      J=0
      JDTWO=JD+JD
      JD3=JDTWO+JD
      DO 5 I=1,NC
      IF (N(I).LT.UMIN) GO TO 5
      ULMAX=AMAX1(ULMAX,L(I))
      J=J+1
C NQ IS AN ARRAY CONTAINING THE INDEX IN N OF COHORTS WHICH ARE NONZERO:
      NQ(J)=I
 5    CONTINUE
C NZ IS THE TOTAL NUMBER OF NON-TRIVIAL COHORTS.
      NZ=J
      IF (J.LE.0 .AND.E.LT.UMIN) GO TO 26
C THE LAST NON-TRIVIAL COHORT TO BE CANNIBALIZED IS NUMBER ICANDQ OUT
C OF THE NZ NON-TRIVIAL COHORTS.
C THE FIRST NON-TRIVIAL COHORT TO CANNIBALIZE IS ICANFQ OUT OF THE NZ
C NON-TRIVIAL COHORTS.
C HLCAND IS AN OVERESTIMATE OF THE MAXIMUM LENGTH OF FISH WHICH CAN BE
C CANNIBALIZED DURING THE NEXT TIME PERIOD.
      ICANFQ=0
      ICANDQ=0
      NOCOH=J.LE.0
      IF (NOCOH) GO TO 11
      JTWO=J+J
      ULCAND=Q2*(ULMAX+HOMAX*(T2-T1))
      HLCAND=ULCAND
      DO 10 I=1,J
      JQ=NQ(I)
      IF(L(JQ).GE.ULCAND) GO TO 7
      ICANDQ=I
      ICAND=JQ
C ICANF IS CALCULATED IN PARMOD. ICANF=P(15)/DTAU+1
 7    IF(JQ.LT.ICANF) ICANFQ=I
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```
      NQ(I+J)=JQ+JD
      NQ(I+JTWO)=JQ+JDTWO
 10   CONTINUE
      ICANFQ=ICANFQ+1
      J=J+JTWO
 11   IF (DOBEV) GO TO 16
C NQ IS AN ARRAY CONTAINING THE INDEX IN V OF ENTITIES BEING INTEGRATED.
      DO 15 I=1,3
      IF (V(I       ).LT.UMIN) GO TO 15
      J=J+1
      NQ(J)=JD3 + I
 15   CONTINUE
 16   IF (.NOT.FISHIN) GO TO 14
      J=J+1
      NQ(J)=JD3 + 4
C- IF VCUM,GCN,ZBS ARE USED IN MODEL, MAYBE CHANGE NOCUM USAGE
 14   IF (NOCUM) GO TO 19
      DO 17 I=2,3
C- IF V(2),V(3) ARE EXTINCT, DO NOT CALCULATE VCUM(1),VCUM(2):
      IF(V(I).LT.UMIN) GO TO 17
      J=J+1
      NQ(J)=JD3+4+I
 17   CONTINUE
 19   KE=J
      CALL MERSON (T1,T2)
      TT=T2
      IF (IER.EQ.0) GO TO 20
      JS=MIN0(IER,7)
      LIER=1H=
      PRINT 18,T1,T2,IER,((SHER(I,J),I=1,5),J=1,JS)
 18   FORMAT (/" ----------WARNING: ACCURACY CRITERION NOT MET BETWEEN "
     & ,F19.14, " AND ",F19.14," ---------- IER="I4/ 3X,"TIME",17X,"I",
     - 5X,"V(I)",12X,"VDOT(I)",9X,"MAX.EST.REL.ERROR",7(/1X,F19.14,1X,
     - F5.0,3(1X,G15.7)))
      IERTOT=IERTOT+IER
C- IER IS RESET IN MERSON
 20   JJ=0
      IF (NOCOH) GO TO 24
      DO 25 KI=1,NZ
      I=NQ(KI)
      IF (N(I).GE.UMIN) GO TO 23
      L(I)=0.
      W(I)=0.
      N(I)=0.
      B(I)=0.
      GCN(I)=0.
      GO TO 25
 23   JJ=I
 25   CONTINUE
C  NC MAY BE REDUCED IN COHUP OR CALC:
 24   NC=JJ
      IF (E.GE.UMIN) RETURN
      IF (RIPEN) E=P(74)
      IF (E.GT.0.) RETURN
      IF (JJ.GT.0) RETURN
 26   DBUG=.TRUE.
      CALL ILLUS(.TRUE.)
C- FILES MAY NEED TO BE CLOSED IN SUBROUTINES SIM OR CALC.
      IF (TT.GE.STPNCH) CLOSE(7,DISP=CRUNCH)
      IF (DD) CLOSE(4,DISP=CRUNCH)
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      CLOSE(9)
      CALL MSTOP( "NO COHORTS,NO EGGS",18)
      END


      SUBROUTINE MERSON(T1,T2)
C- PERFORMS NUMERICAL INTEGRATION
C VERSION FOR POL.     PROGRAMMED BY C.D. KNECHTEL IN FORTRAN IV
C        ---------------DESCRIPTION--------------
C SUBROUTINE MERSON IS A FOURTH ORDER AUTOMATIC STEP CHANGE MERSON
C DIFFERENTIAL EQUATION SOLVER FOR FORWARDS INTEGRATION
C OF ORDINARY, FIRST DEGREE, SIMULTANEOUS DIFFERENTIAL EQUATIONS.
C SEE CHRISTIANSEN(1970), NUMERISCHE MATHEMATIK 14(4): 317-324,
C FOR DETAILS.  IT IS A RUNGE-KUTTA TYPE METHOD.
C      ------------SOME RESULTS PRODUCED BY THE SUBROUTINE------------
C- T,TT-INDEPENDENT VARIABLE, ITS FINAL VALUE EQUALS T2.
C  V -- AN ARRAY.  ITS ELEMENTS CONTAIN THE INTEGRATION RESULTS.
C  VDOT -- AN ARRAY.  ITS ELEMENTS CONTAIN THE DERIVATIVES AT T2.
C  TD -- ADJUSTED STEP SIZE
C  IER.GT.0 MEANS THAT ABS(H) HAS BEEN REDUCED TO HMIN, BUT THE ACCURACY
C  CRITERION STILL HAS NOT BEEN MET.  NONETHELESS, INTEGRATION CONTINUES.
C
C              ---------------PARAMETERS--------------
C  TD -- TIME STEP FOR NUMERICAL INTEGRATION.  TD IS CHANGED TO EQUAL THE
C      FINAL FULL LENGTH STEP SIZE (TD=HS) BEFORE EXITING THE SUBROUTINE.
C- TDIMIN -- THE MINIMUM TD USED SINCE THE LAST PRINT TIME OR EVENT.
C  T1 -- STARTING POINT OF INTEGRATION.  T=T1 AT THE START.
C  T2,Z -- END POINT OF INTEGRATION.  T=Z=T2 AT THE END OF INTEGRATION.
C  V -- ARRAY CONTAINING THE INITIAL VALUES OF DEPENDENT VARIABLES.
C     DER - A SUBROUTINE WHICH EVALUATES THE DERIVATIVES OF V.  DER MAY
C           BE MADE INTO A PARAMETER, IF DESIRED, BUT THEN IT MUST BE
C              DECLARED IN AN EXTERNAL STATEMENT IN THE PROGRAM CALLING
C              THIS SUBROUTINE.
C  H -- A GUESS FOR THE STEP SIZE.  H=TD AT THE START OF INTEGRATION,
C       BUT IT MAY VARY AFTER THAT TIME.
C   TDL -- THE LAST H USED.
C- HMIN,TDMIN -- LOWER BOUND FOR THE STEP SIZE IN ORDER TO PREVENT
C- INDEFINITE CYCLING IN SOME CASES.  A QUESS IS TO TAKE HMIN AS H/100..
C- HMAX,TDMAX - UPPER BOUND FOR STEP SIZE TO PREVENT ERROR UNDERESTIMATE
C  ACCRCY -- DESIRED BOUND FOR RELATIVE ACCURACY.  NOTE THAT E5 EQUALS
C                                  ACCRCY.   IF E5 IS GREATER THAN OR
C            EQUAL TO 1, THE ORIGINAL STEP SIZE WILL NOT BE CHANGED, AND
C            THE ACCURACY  TEST WILL BE DROPPED.
C  REDUCE -- REDUCTION FACTOR WHICH MAY BE USED TO PRODUCE HMIN FROM H.
C  REDUCE IS UNUSED IN THIS VERSION.
C- ND -- NUMBER OF DIFFERENTIAL EQUATIONS IN THE SYSTEM.
C
C            ---------------EXPLANATION OF LOGICAL VARIABLES---------------
C  BC=TRUE - NO ACCURACY CHECK IS MADE, NO STEP SIZE CHANGES ARE MADE.
C  BE=FALSE - DOUBLING THE STEP SIZE PRESENTLY WOULD NOT BE APPROPRIATE.
C- BH=FALSE - DOUBLING STEP SIZE NOT PERMITTED SINCE IT WAS JUST HALVED.
C- BM=TRUE - THE PRESENT STEP SIZE IS .LT. THE MAX STEP SIZE (TDMAX,HMAX
C  BQ=TRUE - THE ACCURACY CRITERION WAS SATISFIED.
C  BR=TRUE - THE NEXT INTEGRATION WON'T REACH THE END OF THE INTERVAL.
C  BX=TRUE -THE MIN STEP SIZE IS IN USE, BUT A LESSER ONE WAS CALCULATED
C
C            ---------------ARRAYS USED IN MERSON-------------
C THE DIMENSION OF ALL ARRAYS MUST EQUAL OR EXCEED ND.  HOWEVER, IF ND IS
C GREATER THAN 67, THE ONLY THING THAT NEEDS TO BE CHANGED IN THIS
C SUBROUTINE IS THE DIMENSION OF THE FOLLOWING ARRAYS:
```

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      DIMENSION       G(67),S(67),U(67)
      DIMENSION UGCN(20)
C  THE DIMENSION OF NQ AND VDOT ALSO WOULD NEED TO BE CHANGED.
C
C           ---------------SIMPLE VARIABLES USED IN MERSON---------------
      LOGICAL BC,BE,BH,BM,BQ,BR,BX
      INTEGER I,IER,J,ND,SW
      REAL ACCRCY,E5,H,HMIN,HS,H3,RQ,R,T,TD,TS,T1,T2,Z
C
C           ---------------COMMON BLOCKS---------------
$INCLUDE "L/I/STATV"
      COMMON /STATE/V(67),KD,ETT,NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL NTT
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
C     ACCRCY=.0005 USUALLY GIVES A SOLUTION ACCURATE TO THREE DIGITS.
C     ACCRCY=.5*(10**(-N)) USUALLY GIVES A SOLUTION ACCURATE TO N DIGITS
C  IER.GT.0 WARNS THAT THE ACCURACY CRITERION WAS NOT ALWAYS MET.
C     HMIN,ACCRCY,TD,REDUCE, AND IER ALL MAY BE MADE INTO
C     PARAMETERS, PUT INTO COMMON, OR SET INTERNALLY IN THIS SUBROUTINE.
C     VDOT MAY ALSO BE MADE INTO A PARAMETER OR PUT IN COMMON.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFG,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
C           ---------------EXECUTABLE STATEMENTS---------------
      IER=0
      JD=KD
      ND=KE
      JD3=3*JD
      UMIN=NMIN
      H=TD
      Z=T2
      T=T1
      HMIN=TDMIN
      HMAX=TDMAX
      E5=ACCRCY
      BC=E5.GE.1
      BM=H.LT.HMAX
      BR=.TRUE.
      BH=.TRUE.
      BX=.FALSE.
```

```
C       IF ACCRCY.GE.1, THEN NO STEP SIZE CHANGES ARE MADE.
 10     DO 15 J=1,ND,1
 15     G(NQ(J)) = V(NQ(J))
        TS=T
C- FOR VARIABLE STEP SIZE, VARIABLES SET BY CALLING DER MIGHT NEED
C- RESETTING IN MERSON, OR ELSE NEED RESETTING IN THE NEXT CALL TO DER.
C- NOCUM SHOULD BE RESET WHENEVER GCN OR ZBS ARE RESET
C- IF VCUM,GCN,ZBS ARE USED IN MODEL, MAYBE CHANGE NOCUM USAGE
        IF (NOCUM) GO TO 20
        UZBS=ZBS
        IF (NOCOH) GO TO 20
        DO 16 J=1,NZ,1
 16     UGCN(NQ(J))=GCN(NQ(J))
 20     HS=H
        RQ=T+H-Z
        BE=.TRUE.
C TEST FOR END OF INTEGRATION RANGE.
        IF (RQ.LT.O.) GO TO 22
        H=Z-T
C- H=Z-T SHORTENS THE STEP SIZE SO WE DO NOT INTEGRATE BEYOND THE END
C-  OF THE INTEGRATION RANGE
        BR=.FALSE.
C  NEXT INTEGRATE ONE STEP.
 22     H3=H/3.
        H5=.5*H
        H6=.5*H3
        TDL=H
        DO 54 SW=1,5
        CALL DER
        DO 137 KI=1,ND
C  THIS IS A MODIFICATION OF THE USUAL METHOD IN ORDER TO ACCOMMODATE
C  SPARSE ARRAYS.
        I=NQ(KI)
        RQ=H3*VDOT(I)
        GO TO (31,32,33,34,35),SW
 31     R=RQ
        U(I)=R
        GO TO 36
 32     R=.5*(RQ+U(I))
        GO TO 36
 33     R=3.*RQ
        S(I)=R
        R=.375*(R+U(I))
        GO TO 36
 34     R=U(I)+4.*RQ
        U(I)=R
        R=1.5*(R-S(I))
        GO TO 36
 35     R=.5*(RQ+U(I))
        RQ=ABS(2.*R-1.5*(RQ+S(I)))
 36     V(I)=  G(I) + R
        IF (SW.LT.5) GO TO 137
        IF (BC) GO TO 49
        R = ABS( V(I) )
C* THE BELOW CONSTANT(1E-5) IS USED IN AGESTA, MERSON, DETECT
C* AVOID INTEGRATING QUANTITIES OFTEN .LT. 1E-5 , ELSE CHANGE BELOW:
        IF (R.GE.1E-5) GO TO 38
        R=E5
        GO TO 39
 38     R=E5*R
```

```
C  TEST FOR REDUCTION OF THE STEP SIZE (IE, DO ACCURACY TEST):
 39    BQ=RQ.LT.R
       IF (BQ.OR.BX) GO TO 47
       BR=.TRUE.
       BM=.TRUE.
       BH=.FALSE.
       H=H5
       IF (H.GE.HMIN) GO TO 41
       BX=.TRUE.
       H=HMIN
 41    TDIMIN=AMIN1(H,TDIMIN)
       DO 43 J=1,ND,1
 43    V(NQ(J)) = G(NQ(J))
       T=TS
       TT=T
C- FOR VARIABLE STEP SIZE, VARIABLES SET BY CALLING DER MIGHT NEED
C- RESETTING IN MERSON, OR ELSE NEED RESETTING IN THE NEXT CALL TO DER.
C- NOCUM SHOULD BE RESET IF GCN OR ZBS ARE RESET OUTSIDE THIS SUBROUTINE
C- IF VCUM,GCN,ZBS ARE USED IN MODEL, MAYBE CHANGE NOCUM USAGE
       IF (NOCUM) GO TO 20
       ZBS=UZBS
       IF (NOCOH) GO TO 20
       DO 44 J=1,NZ,1
 44    GCN(NQ(J))=UGCN(NQ(J))
       GO TO 20
 47    IF (.NOT.BQ.AND.BX) CALL DETECT (TT,I,V(I),VDOT(I),RQ)
       IF(RQ.GE..03125*R) BE=.FALSE.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C THIS ALSO MODIFIES THE USUAL METHOD.  IF A CERTAIN STATE VARIABLE GOES
C BELOW A CERTAIN NONNEGATIVE LIMIT, THAT STATE VARIABLE IS SET TO ZERO.
C  THIS IS DONE AFTER THE ACCURACY TEST, BECAUSE IT REPRESENTS A JUMP
C  DISCONTINUITY.
 49    IF (V(I).GE.UMIN) GO TO 137
C* IF PHY(=V(JD3+1)) IS EVER .LT. NMIN(=UMIN), MAYBE CHANGE BELOW:
       IF (I.LE.JD .OR. I.GT.JD3 .AND. I.LE.JD3+3) V(I)=0.
       IF (I.NE.1) GO TO 137
       PLENTY=.FALSE.
C- IF P(74) SOMEWHAT .GT. NMIN, THEN NO POLLOCK EXTINCTION IS POSSIBLE.
       V(1)=P(74)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 137   CONTINUE
       GO TO (50,54,51,52,54),SW
 50    T=T+H3
       GO TO 53
 51    T=T+H6
       GO TO 53
C-  IF THE BELOW IS CHANGED, CHANGE FORMULA FOR UTLDER IN PRINTR:
 52    T=T+H5
 53    TT=T
 54    CONTINUE
       IF (BC) GO TO 60
C  TEST FOR A POSSIBLE DOUBLING OF STEP SIZE:
       IF(.NOT.(BE.AND.BH.AND.BR.AND.BM)) GO TO 58
       H=AMIN1(HMAX,H+H)
       BM=H.LT.HMAX
       BX=.FALSE.
 58    BH=.TRUE.
 60    IF (BR) GO TO 10
C- CHANGE INITIAL STEP SIZE TO EQUAL FINAL UNSHORTENED STEP SIZE:
       TD=HS
```

```
      RETURN
      END


      SUBROUTINE DETECT(TT, I, UV, UVDOT, RQ)
C- IF NUMERICAL INTEGRATION ACCURACY CRITERION NOT MET, STORES
C- VARIOUS QUANTITIES USEFUL IN FIGURING OUT WHY.
$INCLUDE "L/I/MER"
      COMMON /MER/ACCRCY, IER, LIER, IERTOT, RQMAX, SHER(5, 7), TDMIN, TDIMIN,
     -TDMAX, KE, NZ, NQ(67), VDOT(67)
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
      IF (IER. EQ. 0) GO TO 15
      UI=FLOAT(I)
      JIER=MINO(IER, 7)
      DO 10 J=1, JIER
C- ASSUMED HERE THAT J KEEPS ITS VALUE AFTER EXITING THE DO LOOP:
      IF (UI. EQ. SHER(2, J)) GO TO 12
 10   CONTINUE
      GO TO 15
C* THE BELOW CONSTANT(1E-5) IS USED IN AGESTA, MERSON, DETECT
C- RQ IS FORCED TO BE . GE. 0 IN MERSON
 12   URQ=RQ/AMAX1(ABS(UV), 1E-5)
      IF (URQ. LE. SHER(5, J)) RETURN
      SHER(5, J)=URQ
      GO TO 17
 15   J=MOD(IER, 7)+1
      IER=IER+1
      SHER(2, J)=I
      SHER(5, J)=RQ/AMAX1(ABS(UV), 1E-5)
 17   SHER(1, J)=TT
      SHER(3, J)=UV
      SHER(4, J)=UVDOT
      RQMAX=AMAX1(RQMAX, SHER(5, J))
      RETURN
      END


      SUBROUTINE DER
C- CALCULATES DERIVATIVES
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20), W(20), L(20), PHY, COPE, EUPH, YLD, E, VCUM(2), KD, ETT,
     &NTT, BTT, B(20), B313, TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N, W, L, B, SM, MT, ETC.
      REAL N, NTT, L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MERA"
      COMMON /MER/ACCRCY, IER, LIER, IERTOT, RQMAX, SHER(5, 7), TDMIN, TDIMIN,
     -TDMAX, KE, NZ, NQ(67), NDOT(20), WDOT(20), LDOT(20), VDOT(7)
      REAL NDOT, LDOT
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY, WOO, D2, D4, NMIN, PLENTY, Q2, HLCAND, ICANAQ, IDOF, NOCOH
     -, MT(20), SM(20), RC(20), FD(20), D(17, 20), WL(20), YT, CT, PREDUR, HOMAX,
     -M(20), ICAND, D6, D7, D8, D9, EF, ICANF, ICANE, EGGDUR, ICANFQ, ICANDQ, ZBS,
     -ZM(6), ZLNG(3), ZW(3), IEXIST, FISHIN, F(20), FSTART, CN(20), GCN(20),
     -FCF(20), FCM(20), EATER(20), LAYING, RIPEN, FDU(20), P(120)
      REAL MT, KAY, NMIN, M
      LOGICAL FISHIN, LAYING, NOCOH, PLENTY, RIPEN
$INCLUDE "L/I/CONTRL"
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      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
      WGTDT(UWI,URC)=AMIN1(P(3),P(117)*UWI**P(118))*(URC-P(1)*UWI**P(2))
      JVON=NVON
      IF (NOCOH) GO TO 6
      DO 4 KI=1,NZ
      I=NQ(KI)
C- MT IS ZEROED HERE BECAUSE A LOWER COHORT MAY CANNIBALIZE A HIGHER.
      MT(I)=0.
 4    B(I) = W(I) * N(I)
 6    IF (DOBEV) GO TO 8
      CALL ISV
C- EF IS THE INSTANTANEOUS EGG MORTALITY RATE.
C THE BELOW EQUATION IS WHAT WOULD BE USED TO NUMERICALLY CALCULATE THE
C DERIVATIVE OF E:
C     VDOT(5)=-EF*E
C HOWEVER, SINCE EF IS LARGE, IT IS COSTLY TO NUMERICALLY INTEGRATE E,SO
C E IS CALCULATED ANALYTICALLY IN SUBROUTINE LAYEGG. IF E IS CALCULATED
C NUMERICALLY, USAGE OF E,NZ,J,NQ IN CALC, DER,
C PRINTR, COHUP, AGESTA, AND MERSON MUST BE CHANGED.
C- IF (RIPEN=.TRUE), E MAY AT TIMES NEED TO BE SET TO P(74) IN MERSON.
C* YT IS THE TIME OF THE YEAR.
      YT= AMOD (TT,1.)
C  PHY IS IN UNITS OF GRAMS OF CARBON; COPE AND EUPH ARE GRAMS WET WT.
C  CALCULATE THE CHANGE IN PHYTOPLANKTON BIOMASS(PHY).
      VDOT(1)         = PULSE(YT,P(88) , P(21) , P(32))
     &                + PULSE(YT,P(36) , P(23) , P(33))
     &                + FLTTOP (YT , P(37) , P(24) , P(25) , P(33),P(35))
     &                + PULSE(YT,P(38) , P(25) , P(35))
     &                + P(31) - P(39)*PHY - ZM(1) - ZM(2) - ZM(3)
C  CALCULATE CHANGE IN COPEPOD BIOMASS(COPE)
      VDOT(2)         = P(46)/P(45)*ZM(1) - P(47)*COPE -ZM(4)/P(45)-ZM(5)
      VDOT(6)=COPE
C CALCULATE CHANGE IN EUPHAUSID BIOMASS(EUPH)
      VDOT(3)         = P(56)*(ZM(2)+ZM(4))/P(48) - P(57)*EUPH -ZM(6)
      VDOT(7)=EUPH
 8    UDYLD = 0.
      IF (NOCOH) GO TO 16
      DO 15 KI=1,NZ
      I = NQ(KI)
      LDOT(I)=0.
      WDOT(I)=0.
      NDOT(I)=0.
      IF (B(I).LE.0.) GO TO 15
      UFISH = 0.
C- CALCULATE WEIGHT DEPENDENT MORTALITY RATE (MAY IMITATE PREDATION):
C* FOR THE DOBEV OPTION, P(97) IS SET TO ZERO IN PARMOD
      UPRED=P(97)/(W(I)+P(98))
      IF (.NOT.FISHIN) GO TO 10
      UFISH=F(I)/(1.+EXP((P(84)-L(I))*P(85)))
      UDYLD = UDYLD + B(I)*UFISH
 10   NDOT(I) = -(M(I)+MT(I)+SM(I)+UFISH+UPRED) * N(I)
      IF (I.GT.JVON) GO TO 12
      WDOT(I)=D6
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      LDOT(I)=D9
C  .LT. IS USED BELOW IN CASE P(12).EQ.0.
      IF (L(I).LT.P(77)) GO TO 15
      LDOT(I) = KAY*(D7-L(I))
      WDOT(I) = LDOT(I)*W(I)/L(I)*D2
      GO TO 15
C- CALCULATE LENGTH DERIVATIVES.  IF CHANGED, MAYBE CHANGE THE
C- CALCULATION OF HOMAX, HLCAND.
 12   IF (I.GT.1) GO TO 11
C--  COHORT 1 FISH
C--- CALCULATE POTENTIAL GROWTH IN LENGTH DERIVATIVE:
      LDOT(I)=P(91)
C* CN IS SET IN SUBROUTINE ISV.
C* IF COHORT 1 BREEDS WHILE ITS EATER(1)=0, MAYBE CHANGE BELOW:
      IF(EATER(I).GT.0.)LDOT(I)=P(92)*AMAX1(0.,AMIN1(1.,(CN(I)
     --RCON1(YT))/P(93)))
      IF (PLENTY) GO TO 14
      NDOT(I)=0.
      WDOT(I)=WGTDT(W(I),RC(I))
      IF(CN(I).LT.P(75))WDOT(I)=AMAX1(WDOT(I),0.)
      GO TO 15
C--  COHORT 2 AND OVER
 11   IF (L(I).GT.P(68)) GO TO 13
      LDOT(I)=P(99)*AMAX1(0.,AMIN1(1.,(CN(I)-P(90))/P(100)))
      GO TO 14
 13   LDOT(I)=P(99)*AMAX1(0.,AMIN1(1.,W(I)/
     &(P(104)*L(I)**P(105))-P(106)))
 14   WDOT(I)=WGTDT(W(I),RC(I))
 15   CONTINUE
C  SET THE DERIVATIVE OF THE POLLOCK FISHING YIELD (CATCH):
 16   VDOT(4) = UDYLD
      RETURN
      END


      SUBROUTINE ISV
C  CALCULATE FOOD RESOURCES AND MORTALITIES.
C- ISV HAS 4 SECTIONS. THEY ARE: OTHER POPULATIONS,
C- POLLOCK COHORT 1, POLLOCK NONCANNIBALS, POLLOCK CANNIBALS.
C  PRODUCTS OF ISV ARE RC, FD, MT, ZM, SM, D, WL,CN,GCN, ICANAQ, IEXIST.
C  D,WL,CN,GCN  ARE NOT ALWAYS RESET FOR "TRIVIAL" COHORTS, SO THEY MAY
C  BE NON-ZERO , EVEN THOUGH THEIR ASSOCIATED COHORT NO LONGER EXISTS.
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/MERA"
      COMMON /MER/ACCRCY,IER,LIER,IERTOT,RQMAX,SHER(5,7),TDMIN,TDIMIN,
     -TDMAX,KE,NZ,NQ(67),NDOT(20),WDOT(20),LDOT(20),VDOT(7)
      REAL NDOT,LDOT
C IF COMMON BLOCK /MER/ IS CHANGED, CHANGE COMDECKS L/I/MER AND L/I/MERA
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
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```
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
$INCLUDE "L/I/CONTRL"
      COMMON /CONTRL/ NC,TD,TT,DTAU,TSTP,DOBEV,TP,TF,TL,COMAX,ASTOP,DD,
     -DBUG,TDL,RDWGHT,SHOWB,SHOWD,PCHEND,STPRNT,STPNCH,TPOFF,NVON,NOCUM
      COMMON/GRAPH/ DOGRPH,NGR,IGR(32),IFILE(32),NFILE,SCALM(7),ITRAN(7)
     -,SCALC(7),IGL(7),IHD(7),IHDEC(7)
      INTEGER TSTP,COMAX
      LOGICAL DBUG,RDWGHT,SHOWB,SHOWD,DOGRPH,PCHEND,DOBEV,NOCUM,ASTOP,DD
      COMMON/EVENT/CYCLE,CYOFF,AOFF,ISEQ,NEV,IEV(32),TEV(32),NXTEV(33)
      REAL NXTEV
C- SECTION 1, OTHER POPULATIONS: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      ZM(3)=0.
      ZM(5)=0.
      ZM(6)=0.
      CALL FDCHAI
      IF (NOCOH) RETURN
C- SECTIONS 2 THROUGH 4, POLLOCK: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C ICANDQ AND ICANFQ ARE CALCULATED IN CALC.
      JDQ=ICANDQ
      JJ=ICANFQ
C NQ(JJ) IS THE FIRST COHORT THAT MAY CANNIBALIZE.
C  NQ(JDQ) IS THE LAST COHORT TO POSSIBLY BE CANNIBALIZED.
      JAQ=JDQ+1
      JEXIST=JAQ
      DO 200 KI=1,JDQ
      I=NQ(KI)
      IF (B(I).LE.0.) GO TO 200
      JEXIST=MINO(JEXIST,KI)
      IF (L(I).GT.P(65)) JAQ = MINO(JAQ,KI)
C  JAQ,ICANAQ POINT TO THE FIRST COHORT AVAILABLE TO CANNIBALISM
 200  CONTINUE
      IEXIST=JEXIST
      ICANAQ=JAQ
      IDOF=NZ+1
C NQ(JB) IS  THE LAST COHORT NOT TO CANNIBALIZE.
      JB=JJ-1
C- SECTION 2, POLLOCK COHORT 1: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C CHECK WHETHER THERE ARE ANY FISH IN THE FIRST COHORT.
      JCOH = JEXIST
      I=1
      SM(I)=0.
      RC(I)=0.
      FD(I)=0.
      IF(NQ(JEXIST).GT.I) GO TO 4
      JCOH=2
C JCOH POINTS TO THE FIRST COHORT FOR WHICH FOOD HAS NOT BEEN CALCULATED
      WL(I)=P(80)*L(I)**P(63)
C- IF EXPONENT 3 IS CHANGED BELOW, THEN CHANGE THE DEFINITION AND
C- CALCULATION OF P(4), P(70), AND THEIR USE IN SUBROUTINES LAYEGG, ISV.
      IF (L(I).GT.P(4)) WL(I)=P(70)*L(I)**3
      CN(I)=W(I)/WL(I)
      GCN(I)=AMAX1(GCN(I),CN(I))
      D(1,I)=0.
      D(2,I)=0.
      D(3,I) = 0.
      IF (CN(I).LT.P(83))SM(I)=P(82)*(P(83)-CN(I))**P(81)
C CHECK WHETHER COHORT 1 IS OLD ENOUGH TO HAVE STARTED EATING.
      IF (EATER(I).LE.0.) GO TO 2
C I ASSUME POLLOCK IN THE FIRST COHORT DO NOT CANNIBALIZE, BUT MAY EAT
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C PHYTOPLANKTON, COPEPODS, AND EUPHAUSIDS. I ASSUME THEY ARE THE ONLY
C POLLOCK WHICH MAY EAT PHYTOPLANKTON.
C ZW(I) IS THE "AVERAGE" WEIGHT OF ONE INDIVIDUAL OF SPECIES I.
C I ASSUME PHYTOPLANKTON IS ALWAYS SMALL ENOUGH TO EAT.
      D(1,I) = SEL(WL(I),ZW(1),L(I)) * P(60)*PHY
C  Q2 IS UNUSED BELOW TO COMPENSATE FOR MANY COPEPODS AND EUPHAUSIDS
C  BEING SMALLER THAN THEIR "STANDARD" SIZE:
      D(2,I) = SEL(WL(I),ZW(2),L(I)) * COPE
      D(3,I) = SEL(WL(I),ZW(3),L(I)) * EUPH
      UFF = D(1,I) + D(2,I) + D(3,I)
      UWS=W(I)**P(101)
      UP9=P(9)*UWS
      IF(UFF.LE.UP9) GO TO 2
C-  PERFORM POLLOCK PREY SWITCHING
      UFFU=P(76)*UFF
      UFF = P(67)*UFF
      IF (D(1,I).LT.UFFU) CALL PSWTCH(D(1,I),UFF,UFFU)
      IF (D(2,I).LT.UFFU) CALL PSWTCH(D(2,I),UFF,UFFU)
      IF (D(3,I).LT.UFFU) CALL PSWTCH(D(3,I),UFF,UFFU)
      FD(I) = D(1,I) + D(2,I) + D(3,I)
      IF (FD(I).LE.UP9) GO TO 2
      RC(I)=FOOD(FD(I),P(7),P(8)*UWS,UP9)*EATER(I)*L(I)**P(119)
C CALCULATE MORTALITIES.
      UB = RC(I)*N(I)/FD(I)
C PHYTOPLANKTON MORTALITY.
      ZM(3) = ZM(3) + UB*D(1,I)/P(40)
C COPEPOD MORTALITY.
      ZM(5) = ZM(5) + UB*D(2,I)
C EUPHAUSID MORTALITY.
      ZM(6) = ZM(6) + UB*D(3,I)
C- THE BELOW MIGHT BE CHANGED IF THERE IS MORE THAN ONE AGE 0 COHORT.
 2    IF (NZ.EQ.I) RETURN
C- SECTION 3, POLLOCK NONCANNIBALS: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C- CHECK IF THERE IS ANYTHING TO CANNIBALIZE (AND MAYBE EXIT SECTION):
 4    IF (JAQ   .GT.JDQ   .OR.   P(5).LE.0.) JB=NZ
      IF (JCOH.GT.JB) GO TO 5
C CALCULATE FOOD FOR THE NONCANNIBALIZING COHORTS.
      DO 3 KI=JCOH,JB
      I=NQ(KI)
      SM(I)=0.
      RC(I)=0.
      FD(I)=0.
      IF (B(I).LE.0.) GO TO 3
C- IF EXPONENT 3 IS CHANGED BELOW, THEN CHANGE THE DEFINITION AND
C- CALCULATION OF P(4), P(70), AND THEIR USE IN SUBROUTINES LAYEGG, ISV.
      WL(I)=P(70)*L(I)**3
      IF (L(I).LT.P(4)) WL(I)=P(80)*L(I)**P(63)
      CN(I)=W(I)/WL(I)
      GCN(I)=AMAX1(GCN(I),CN(I))
      IF (CN(I).LT.P(73))SM(I)=P(72)*(P(73)-CN(I))**P(71)
      IF (EATER(I).LE.0.) GO TO 3
      D(2,I)=0.
      D(3,I) = 0.
      UQ2= Q2*L(I)
C CALCULATE AVAILABLE COPEPODS.
      IF (ZLNG(2).LE.UQ2) D(2,I) = SEL (WL(I),ZW(2),L(I))*COPE
C CALCULATE AVAILABLE EUPHAUSIDS.
      IF (ZLNG(3).LE.UQ2) D(3,I) = SEL (WL(I),ZW(3),L(I))*EUPH
      UFF = D(2,I) + D(3,I)
      UWS=W(I)**P(102)
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      UP9=P(19)*UWS
      IF (UFF.LE.UP9) GO TO 3
C-  PERFORM POLLOCK PREY SWITCHING
      UFFU=P(76)*UFF
      UFF = P(67)*UFF
      IF (D(2,I).LT.UFFU) CALL PSWTCH(D(2,I),UFF,UFFU)
      IF (D(3,I).LT.UFFU) CALL PSWTCH(D(3,I),UFF,UFFU)
      FD(I) = D(2,I) + D(3,I)
      IF (FD(I).LE.UP9) GO TO 3
      RC(I) = FOOD (FD(I),FDU(I),P(18)*UWS , UP9)*EATER(I)*L(I)**P(119)
      UB = RC(I)*N(I)/FD(I)
C COPEPOD MORTALITY.
      ZM(5) = ZM(5) + UB*D(2,I)
C EUPHAUSID MORTALITY.
      ZM(6) = ZM(6) + UB*D(3,I)
 3    CONTINUE
C- SECTION 4, POLLOCK CANNIBALS: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C CALCULATE FOOD FOR THE CANNIBALIZERS
 5    IF (JB.GE.NZ) RETURN
      JJ=JB+1
      IDOF=JJ
      DO 20 KI=JJ,NZ
      I=NG(KI)
      SM(I)=0.
      RC(I)=0.
      FD(I)=0.
      IF (B(I).LE.0.) GO TO 20
C- IF EXPONENT 3 IS CHANGED BELOW, THEN CHANGE THE DEFINITION AND
C- CALCULATION OF P(4), P(70), AND THEIR USE IN SUBROUTINES LAYEGG, ISV.
      WL(I)=P(70)*L(I)**3
      IF (L(I).LT.P(4)) WL(I)=P(80)*L(I)**P(63)
      CN(I)=W(I)/WL(I)
      GCN(I)=AMAX1(GCN(I),CN(I))
      IF (CN(I).LT.P(73))SM(I)=P(72)*(P(73)-CN(I))**P(71)
      IF (EATER(I).LE.0.) GO TO 20
      D(2,I)=0.
      D(3,I) = 0.
      UG2= G2*L(I)
C CALCULATE AVAILABLE COPEPODS.
      IF (ZLNG(2).LE.UG2) D(2,I) = SEL (WL(I),ZW(2),L(I))*COPE
C CALCULATE AVAILABLE EUPHAUSIDS.
      IF (ZLNG(3).LE.UG2) D(3,I) = SEL (WL(I),ZW(3),L(I))*EUPH
      UFF = D(2,I) + D(3,I)
C  IF MORE THAN FIRST 14 POLLOCK COHORTS MAY BE CANNIBALIZED, THEN
C  THE FIRST DIMENSION OF D MAY NEED TO BE CHANGED (IE, IF ICAND.GT.14).
      DO 30 KJ=1 ,JDG
      J=NG(KJ)
      D(J+3,I) = 0.
      IF (L(J).GT.UG2 .OR. L(J).LE.P(65) .OR. B(J).LE.0.) GO TO 30
      D(J+3,I)=SEL(WL(I),W(J),L(I))*AMIN1(P(5),(L(J)-P(65))
     * *P(66))*B(J)
      UFF = UFF + D(J+3,I)
 30   CONTINUE
      UWS=W(I)**P(102)
      UP9=P(19)*UWS
      IF (UFF.LE.UP9) GO TO 20
C-  PERFORM POLLOCK PREY SWITCHING
      UFFU=P(76)*UFF
      UFF = P(67)*UFF
      IF (D(2,I).LT.UFFU) CALL PSWTCH(D(2,I),UFF,UFFU)
```

```
      IF (D(3,I).LT.UFFU) CALL PSWTCH(D(3,I),UFF,UFFU)
      FD(I) = D(2,I) + D(3,I)
      DO 35 KJ=JAQ,JDQ
      J3=NQ(KJ) + 3
      IF (D(J3,I).LT.UFFU) CALL PSWTCH(D(J3,I),UFF,UFFU)
      FD(I) = FD(I) + D(J3,I)
 35   CONTINUE
      IF (FD(I).LE.UP9) GO TO 20
      RC(I) = FOOD (FD(I),FDU(I),P(18)*UWS , UP9)*EATER(I)*L(I)**P(119)
      UB = RC(I)*N(I)/FD(I)
C COPEPOD MORTALITY.
      ZM(5) = ZM(5) + UB*D(2,I)
C EUPHAUSID MORTALITY.
      ZM(6) = ZM(6) + UB*D(3,I)
C- CALCULATE POLLOCK MORTALITY DUE TO CANNIBALISM:
      DO 40 KJ = JAQ    ,JDQ
      J = NQ(KJ)
      IF (D(J+3,I).GT.O.) MT(J) = MT(J) + UB*D(J+3,I)/B(J)
 40   CONTINUE
 20   CONTINUE
      RETURN
      END


      SUBROUTINE FDCHAI
C  CALCULATE MORTALITIES (MEASURED IN GRAMS CARBON) OF PHYTOPLANKTON,
C  COPEPODS, AND EUPHAUSIDS - EXCEPT FOR MORTALITIES CAUSED BY POLLOCK.
C  FDCHAI IS CALLED FROM ISV.
$INCLUDE "L/I/STATE"
      COMMON/STATE/N(20),W(20),L(20),PHY,COPE,EUPH,YLD,E,VCUM(2),KD,ETT,
     &NTT,BTT,B(20),B313,TCUM
C  KD (SET IN INPUTR) MUST EQUAL THE DIMENSION OF N,W,L,B,SM,MT, ETC.
      REAL N,NTT,L
C IF COMMON BLOCK /STATE/ IS CHANGED, COMDECKS L/I/STATE, L/I/STATA,
C L/I/STATB, L/I/STATV, AND USE OF B IN AGESTA, SHOW MAY NEED CHANGING.
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
      ZBS=AMIN1(COPE+EUPH,ZBS)
C  CALCULATE PHYTOPLANKTON MORTALITY DUE TO COPEPODS:
      ZM(1) = O.
      UCC = P(41) - PHY*P(42)
      COPEC=P(45)*COPE
C   CALCULATE AN IVLEV FEEDING CURVE WHICH IS OFFSET FROM THE ORIGIN (IE
C   WITH A NON-NEGATIVE X-AXIS INTERCEPT).
      IF (UCC.LT.O.)  ZM(1) = P(43)*COPEC * (1. - EXP(P(44)*UCC))
C  CALCULATE PHYTOPLANKTON AND COPEPOD MOTALITIES DUE TO EUPHAUSIDS:
C  I ASSUME AN EUPHAUSID PRACTICES PREY SWITCHING, AND THAT IT WILL
C  CONSUME SOLELY THAT PREY WHICH IT CAN EAT THE MOST OF. CALCULATIONS
C  ARE PERFORMED IN TERMS OF GRAMS CARBON.
      EUPHC = EUPH*P(48)
C   CALCULATE A FEEDING CURVE ON PHYTOPLANKTON WHICH IS RECTILINEAR,
C   WITH A NON-NEGATIVE X-AXIS INTERCEPT:
      ZM(2)=O.
      UFE=P(54)*PHY
```

```
      IF (UFE.GT.P(53))ZM(2)=EUPHC*FOOD(UFE,P(51),P(52),P(53))
C   CALCULATE A SIMILAR FEEDING CURVE ON COPEPODS:
      ZM(4)=0.
      UFE=P(55)*COPEC
      IF (UFE.GT.P(69))ZM(4)=EUPHC*FOOD(UFE,P(49),P(50),P(69))
C   PERFORM THE PREY SWITCHING:
      I=2
      IF (ZM(2).GT.ZM(4))  I=4
      ZM(I) = 0.
      RETURN
      END


      FUNCTION PULSE (XT,XA,XB,XC)
C  PULSE CALCULATES A DIFFERENTIABLE AND ANALYTICALLY INTEGRABLE PULSE.
      DATA TWOPI /6.2831853071796/
      PULSE = 0.
      IF (XT.LE.XB  .OR.  XT.GE.XB+XC) RETURN
      PULSE = XA/XC*(1. - COS(TWOPI/XC*(XT-XB)))
      RETURN
      END


      FUNCTION FLTTOP (XT,XA,XB,XC,XD,XE)
C  FLTTOP CALCULATES A "BELL-SHAPED" CURVE WITH A FLAT TOP.
C  FLTTOP IS ANALYTICALLY INTEGRABLE AND DIFFERENTIABLE.
      DATA PI /3.1415926535898/
      FLTTOP = 0.
      IF (XT.LE.XB-XD  .OR.  XT.GE.XC+XE)  RETURN
      FLTTOP = XA/(XC-XB)
      IF (XB.LE.XT  .AND.  XT.LE.XC)  RETURN
      IF (XT.LT.XB) GO TO 20
      FLTTOP = .5*FLTTOP*(1. - COS(PI/XE*(XT - XC - XE)))
      RETURN
 20   FLTTOP = .5*FLTTOP*(1. - COS(PI/XD*(XT - XB + XD)))
      RETURN
      END


      SUBROUTINE PSWTCH(XX,CUTLEF,CUTRIG)
C- PERFORMS PREY SWITCHING
C* PSWTCH SHOULD BE CALLED ONLY IF XX.LT.CUTRIG .
      IF (XX.LE.CUTLEF) GO TO 10
      XX=(XX-CUTLEF)/(CUTRIG-CUTLEF)*XX
      RETURN
 10   XX=0.
      RETURN
      END


      FUNCTION FOOD(UFD,P7,P8,P9)
C* CALCULATES A RECTILINEAR FEEDING FUNCTION.
C- USED FOR POLLOCK AND EUPHAUSIDS.
C*  P7 IS THE MAXIMUM FEEDING "RATE"
C*  P8 IS THE CRITICAL VALUE FOR BEGINNING THE MAXIMUM FEEDING RATE.
C*  P9 IS THE CRITICAL VALUE FOR THE CESSATION OF FEEDING.
C* BE SURE TO TEST THAT UFD.GT.P9 BEFORE USING FUNCTION FOOD:
      FOOD=P7
      IF (UFD.GE.P8) RETURN
      FOOD=P7*(UFD-P9)/(P8-P9)
```

```
      RETURN
      END

      FUNCTION RCON1(XYT)
C--- CALCULATE FATNESS REQUIRED BEFORE FISH CAN GROW IN LENGTH
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
      RCON1=P(89)
      IF (XYT.GE.P(103) .AND.  XYT.LE.P(94)) RETURN
      RCON1=P(96)
      IF (XYT.GE.P(95) .OR.  XYT.LT.P(103)) RETURN
      RCON1=(P(96)-P(89))*(XYT-P(94))/(P(95)-P(94))+P(89)
      RETURN
      END

      FUNCTION STEPR1(XX,CUTLEF,CUTRIG,ULEFT,URIGHT)
C* CALCULATE A RECTILINEAR FUNCTION.
      STEPR1=URIGHT
      IF (XX.GE.CUTRIG) RETURN
      STEPR1=ULEFT
      IF (XX.LE.CUTLEF) RETURN
      STEPR1=(URIGHT-ULEFT)*(XX-CUTLEF)/(CUTRIG-CUTLEF)+ULEFT
      RETURN
      END

      FUNCTION SEL(WPRED,WPREY,LPRED)
C* CALCULATE A SIZE SELECTIVITY CURVE
      REAL LPRED
$INCLUDE "L/I/ISV"
      COMMON /ISV/ KAY,WOO,D2,D4,NMIN,PLENTY,Q2,HLCAND,ICANAQ,IDOF,NOCOH
     -,MT(20),SM(20),RC(20),FD(20),D(17,20),WL(20),YT,CT,PREDUR,HOMAX,
     -M(20),ICAND,D6,D7,D8,D9,EF,ICANF,ICANE,EGGDUR,ICANFQ,ICANDQ,ZBS,
     -ZM(6),ZLNG(3),ZW(3),IEXIST,FISHIN,F(20),FSTART,CN(20),GCN(20),
     -FCF(20),FCM(20),EATER(20),LAYING,RIPEN,FDU(20),P(120)
      REAL MT,KAY,NMIN,M
      LOGICAL FISHIN,LAYING,NOCOH,PLENTY,RIPEN
      SEL=EXP((ALOG(WPRED/WPREY)
     * -STEPR1(LPRED,P(112),P(113),P(78),P(58)) )**2
     * *AMAX1(P(79)-P(16)*LPRED , P(59)))
      RETURN
      END
```

APPENDIX D

SAMPLE INPUT FILE FOR COMPUTER PROGRAM

This file contains the reference set of parameters and initial conditions.

When a percent symbol (%) occurs in this file, all characters from that point until a comma or end of line are ignored by the computer program.

```
THE REFERENCE SET OF PARAMETERS AND INITIAL CONDITIONS
1., 21
2, .24609375   %START BREED  %APR.1 ELAPSED DAYS=90     0000 HOURS
3, .3095703125 %LAY EGGS %APR.23
5, .328125     %END BREED    %MAY 1 ELAPSED DAYS=120    0000 HOURS
1, .3642578125 %PRINT
8, .3642578125 %FISHING ENDS
7, .3642578125 %FISHING BEGINS
4, .3642578125 %COHORT UPDATE;EGGS HATCH %MAY 13
1, .3896484375 %PRINT
6, .3896484375 %POLLOCK LARVAE BEGIN EATING %MAY 22
1, 0.                      %JAN.1 ELAPSED DAYS=0      0000 HOURS
1, .0849609375             %FEB.1 ELAPSED DAYS=31     0000 HOURS
1, .1611328125             %MAR.1 ELAPSED DAYS=59     0000 HOURS
1, .24609375               %APR.1 ELAPSED DAYS=90     0000 HOURS
1, .328125                 %MAY 1 ELAPSED DAYS=120    0000 HOURS
1, .4130859375             %JUN.1 ELAPSED DAYS=151    0000 HOURS
1, .4951171875             %JUL.1 ELAPSED DAYS=181    0000 HOURS
1, .580078125              %AUG.1 ELAPSED DAYS=212    0000 HOURS
1, .6650390625             %SEP.1 ELAPSED DAYS=243    0000 HOURS
1, .7470703125             %OCT.1 ELAPSED DAYS=273    0000 HOURS
1, .83203125               %NOV.1 ELAPSED DAYS=304    0000 HOURS
1, .9140625                %DEC.1 ELAPSED DAYS=334    0000 HOURS
```

```
&CTRLRD
TF=.6650390625, TL=55.6650390625, STPRNT=51.665,     STPNCH=999.,
DD=.TRUE., PCHEND=.TRUE., DOBEV=.FALSE., RDWGHT=.TRUE.,
TP=1000.,
TPOFF=-1., DOGRPH=.TRUE., SHOWB=.TRUE., SHOWD=.TRUE., DBUG=.FALSE.,
TD=.03125,         TDMIN=.00048828125, TDMAX=.5,  ACCRCY=.005,
DTAU=1.,    NC=18,  COMAX=20,  NVON=0,
&END
     0.0000 18.0             .23600000E+09.23200000E+09.60000000E+09.0
.30000E+09.88459E+00 5.833.21300E+07.57342E+0220.159.76302E+06.23723E+0332.481
.40748E+06.47429E+03 40.99.21794E+06.70683E+03 46.87.11638E+06.90519E+03 50.93
.34797E+05.10618E+04 53.74.14308E+05.11799E+04 55.67.59806E+04.12663E+04 57.01
.22535E+04.13285E+04 57.94.89706E+03.13725E+04 58.57.35813E+03.14035E+04 59.02
.14236E+03.14252E+04 59.32.56883E+02.14403E+04 59.53.22676E+02.14508E+04 59.68
.90190E+01.14581E+04 59.78.36121E+01.14631E+04 59.85.14346E+01.14666E+04 59.89

&PARP
P(1)=4.0,    P(2)=.8,   P(3)=.84,
P(5)=1.,     P(6)=230.2,
P(7)=.107,   P(8)=.5E9,   P(9)=.6E8,
P(10)=.00087,      P(11)=1.,
P(12)=.25,   P(13)=.0003136,    P(14)=.466,     P(15)=1.,    P(16)=.01,
P(17)=.107,     P(18)=.5E9,        P(19)=.6E8,     P(20)=.5,
P(21)=59.,  P(22)=120.,  P(23)=90.,  P(24)=151.,  P(25)=243.,  P(26)=304.,
P(27)=1.052E9,       P(28)=5.217E9,       P(29)=2.192E9,       P(30)=3.025E9,
P(31)=.8001E9,
P(39)=36.82,  P(40)=20.,  P(41)=.285E9,  P(42)=1.,  P(43)=160.,
P(44)=.73E-9,      P(45)=.052,     P(46)=.8,       P(47)=5.32,
P(48)=.072,     P(49)=60.,      P(50)=.1375E9,     P(51)=54.5,
P(52)=.4466E10,    P(53)=.4252E9,    P(54)=1.,       P(55)=1.,
P(56)=.84,      P(57)=9.1,       P(58)=6.4,  P(59)=-.166,         P(60)=0.,
P(61)=1.,   P(62)=1.,     P(63)=3.579,       P(64)=.1E11,
P(65)=.57,         P(66)=3.5,      P(67)=.01,      P(68)=44.1686,
P(69)=.393E8,  P(70)=.0075,  P(71)=2.,  P(72)=9000.,  P(73)=.75,
P(74)=0.,
P(75)=.6,     P(76)=.06,
P(78)=6.4,        P(79)=-.02,          P(80)=.00168,
P(81)=2.,         P(82)=9000.,           P(83)=.75,
P(84)=40.,    P(85)=.463,     P(86)=.01,     P(87)=.99,
P(89)=.75,      P(90)=1.05,          P(91)=2.1915,       P(92)=35.,
P(93)=.3,       P(94)=.7470703125,  P(95)=.83203125,  P(96)=1.,
P(97)=.04914,      P(98)=.0011,       P(99)=35.,        P(100)=.1,
P(101)=-.15,       P(102)=-.15,
P(104)=5.98E-5,       P(105)=3.66765,       P(106)=10.5,
P(107)=-725.947,    P(108)=-.224,    P(109)=-867.088,   P(110)=-.209,
P(111)=47.5,      P(112)=25.,     P(113)=55.,       P(114)=.107,
P(115)=1.,     P(116)=1.,
P(117)=.79,     P(118)=-.15,     P(119)=2.95,
&END
&PARS
KAY=.37,  D2=2.977,  D4=.18,  D7=60.,  D8=.0075,  NMIN=1.,
PLENTY=.TRUE.,  Q2=.46,
ZLNG=35E-4,     .46,    1.5,     ZW=2.65E-8,     .0025,     .047,
EF=38.,
M=4*.2,.3,6*.4,.7,1.,7*1.3,
F=20*.3,
FISHIN=.TRUE., FSTART=.3642578125,      ICANE=3,
&END
4,    10.,2,12.5,    10.,2,12.5,    10.,2,12.5,    1.3333333,1,11.5
20,   0,11,  0,11,  64,11,  92,11,  65,11,  61,12,  62,12,  63,12,
72,13,  73,13,  74,13,  75,13,  79,13,  83,13,
41,14,  42,14,  43,14,  44,14,  48,14,  52,14
A=NTT-N(1),B=NO.BREEDERS,C=YLD,D=B313,E=EGGS,F=PHY,G=COPE,H=EUPH,
I=B(1),J=B(2),K=B(3),L=B(4),M=B(8),N=B(12),O=L(1),P=L(2),Q=L(3),R=L(4),
S=L(8),T=L(12),
```