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Fisheries Center**

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# **MARINE ECOSYSTEM SIMULATION FOR FISHERIES MANAGEMENT**

July 1979

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MARINE ECOSYSTEM SIMULATION

FOR FISHERIES MANAGEMENT

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## MARINE ECOSYSTEM SIMULATION FOR FISHERIES MANAGEMENT

### 1. A simple view of a complex system

The marine ecosystem, which is invisible to the human eye, is complex in respect to its species composition as well as in respect to processes occurring within it. One of the processes which controls the ecosystem to a large extent is predation, i.e. one species uses the other as food. That big fish eat small fish was well known to scientists centuries ago as shown on Figure 1. Multitudes of other



Figure 1.-- GRANDIBUS EXIGUI SUNT PISCES PISCIBUS ESCA  
(small fish are food for big fish)

processes are at work in the marine ecosystem, such as reproduction (spawning), recruitment, seasonal migrations, and others. There are also the apex predators such as man and his kindred beasts who remove part of the biota from the system, depositing the remains of it in various forms far from the areas of take.

The marine ecosystem is not stable, but considerable fluctuations in abundance and distribution of many species occur. The determination of abundance and fluctuations in abundance and distribution of commercially important species and

factors controlling these fluctuations is one of the main tasks of fisheries scientists. On the other hand, the complex processes controlling the abundance of species in the marine ecosystem run a steady course over long time periods. It is quite remarkable that from about 200,000 eggs, released during spawning time by a female pollock, an average of only 2 fish survive say to age of four. However, deviations from this remarkably constant process of reducing the numbers of survivors occurs, so that a given year class strength of any given species can be few to few tens of times higher than the average. One of the consequences of stronger adult year class of e.g. pollock or cod would be that they would eat more herring, thus the herring population would decrease as the result of increased predation pressure.

The fluctuations in the abundance of species can be caused by numerous factors, such as environmental anomalies and/or factors inherent in the populations themselves (e.g. cannibalism). Although the populations of some species can decrease and others increase with time, the standing stock of the total biomass of finfish fluctuates relatively little in the course of the time; its abundance being determined by the total availability of food, where the zooplankton and benthos productions take a buffering role, determining the so-called "carrying capacity" of any given region.

Obviously fishery will cause changes in the abundance not only in the target species, but also in other species not subject to fishery. These secondary changes can be caused by changes in predation as will be shown with a few examples later in this summary. Furthermore, some changes in target species can be caused by other factors than fishery also (e.g. by environmental anomalies).

In order to form a quantitative picture of the changes and interactions in the marine ecosystem it is necessary to assemble all available knowledge of this system into simulation models, which can be handled only on large computers. This summary attempts to give a birdseye view of the ecosystem simulations and their application in fisheries management problems.

2. The single species fisheries models leading to multispecies approach.

The single species population dynamics models for fisheries evolved in the 1950's, culminating in Beverton and Holt's (1957) development of the comprehensive treatise on the subject. Numerous minor changes, improvements, and additions have been suggested later, some of which have found application as auxiliary methods, such as cohort or virtual population analysis. As computers were not available to fisheries scientists in the 1950's, Beverton and Holt had to weigh the importance of factors to be considered in the formulations of the dynamics and had to make decisions on what to include and what to leave out from these formulations. The detailed consideration of predation (and the predation of one species upon another) was included in one parameter - M - the "natural mortality", partly because a detailed computation of predation is a formidable task for manual computation and partly because the, in space and time variable, composition of food of the species was not well known at this time.

Single species models treat each species separately as if the other species would not exist and no species exercises any influence on the other. Beverton and Holt's (1957) single species assessment model is based on three formulas:

$$dN/dt = - (F+M)N(t) \quad 1$$

$$dw/dt = Hw(t)^{2/3} - kw(t) \quad 2$$

$$dY/dt = FN(t)w(t) \quad 3$$

where t is time, N-number of fish, w-body weight, Y-yield, F-fishing mortality, M-natural mortality, H-food requirement for growth parameter, and k-food requirement for metabolism parameter.

The greatest shortcoming in the application of the above formulation is the lack of data for determination of M-the "natural mortality". As we know now the "natural mortality" is largely a function of age and size of the fish; the greatest part of M in juvenile ages is predation mortality and in adult age the spawning stress and "old age and disease" mortality.

The roundfish landings from the intensively fished North Sea increased in the 1960's, but surprisingly the biomass (stock) also increased (Figure 2). No single

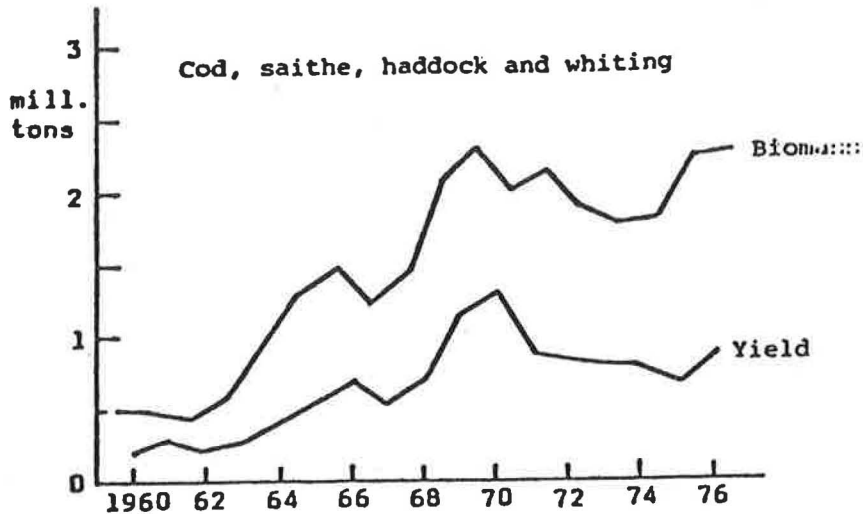


Fig.2.--Stock biomass and yield of cod, saithe, haddock, and whiting in the North Sea from 1960 to 1976 (Ursin, 1979).

species model predicts this biomass increase, as when fishery increases stock decreases according to these models (see Figure 4 as an example of single species model for cod from the North Sea). On the other hand, the stocks of mackerel and herring decreased at the same time in the North Sea (Figure 3) due to intensive

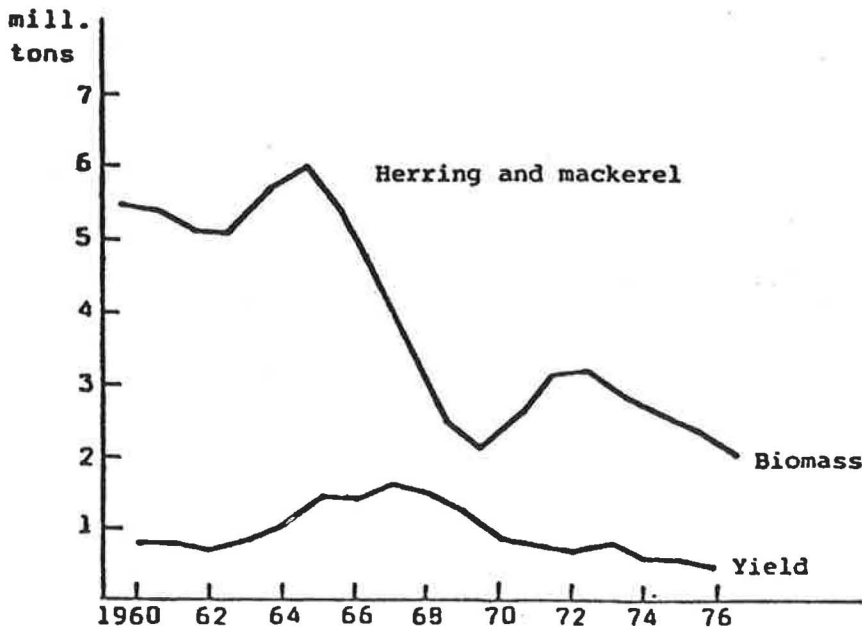


Fig.3.--Stock and yield of herring and mackerel in the North Sea from 1960 to 1976 (Ursin, 1979).



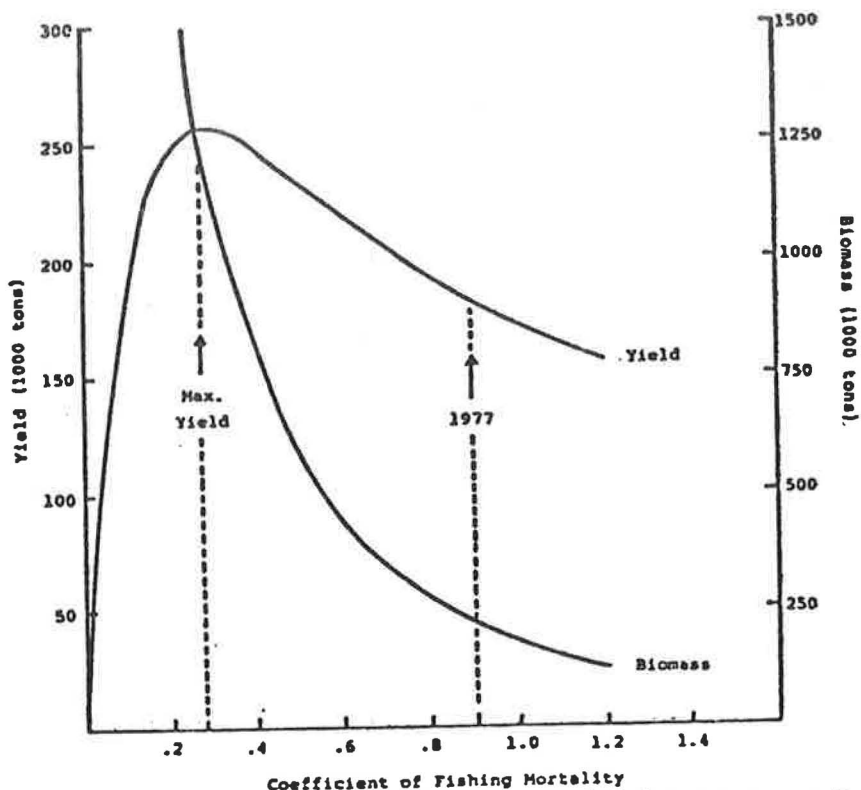


Fig 4 Traditional Beverton and Holt assessment for North Sea cod (Ursin, 1979).

Norwegian fishery on these species. Thus it appeared to Andersen and Ursin from Denmark that mackerel and herring might have been preying on roundfish larvae and when the stocks of mackerel and herring decreased, more roundfish larvae got a chance to survive. Andersen and Ursin (1977) added one more basic term to Beverton and Holt's (1957) basic formulas.

$$dR/dt = f(t)hw(t)^{2/3}$$

4

where R is accumulating food consumed, f is a variable feeding level, and h is a coefficient.

Andersen and Ursin (1977) developed an extensive multispecies model applicable to modern fisheries management problems. With this model they were able to show for example that if fishing effort on cod was reduced to 30% of present level (i.e. to achieve maximum yield with minimum effort according to single species

model - Figure 4), the biomass of cod would increase fourfold (not sixfold as predicted by single species model), but without any increase in yield. However, the stocks of medium sized species, which are important commercial food fish, would shrink to half of their present stock size, mainly due to predation by cod, according to Andersen and Ursin model.

3. The Northwest and Alaska Fisheries Center's ecosystem models (PROBUB and DYNUMES).

The NWAFC ecosystem simulation models (Laevastu and Favorite, 1978a and 1978b) were developed independently from the Danish model without prior knowledge of the latter. Obviously there are some differences and some similarities in approaches in these models; not necessarily in the results, which should be quite comparable if applied to the same problems. The basic difference is that the Danish model is number based whereas NWAFC models are biomass based. This difference causes, for example, considerable difference in treatment of recruitment. The Danish model obtains the initial input of year class strength in numbers from single species considerations and from cohort analysis and computes to a steady state solution with this given input. Furthermore, the Danish model has no spatial resolution.

The NWAFC's PROBUB model (Prognostic Bulk Biomass model) searches for a unique solution with a given set of inputs--i.e. determines the abundance of various species biomasses in a defined equilibrium state. This is a necessity in the NE Pacific, as other methods (single species cohort analyses) are not fully applicable in this area due to several conditions such as underexploitation by man and high amounts of apex predators (marine mammals). In prognostic mode the PROBUB model allows the determination of various fluctuations in abundance of

species caused by environmental anomalies as well as by fishing. The DYNUMES model (Dynamical Numerical Marine Ecosystem model) of NWAFC has spatial resolution (Figure 5) which allows, among others, the simulation of seasonal migrations and their effect, including spatial and temporal variation of composition of food (re. predation).

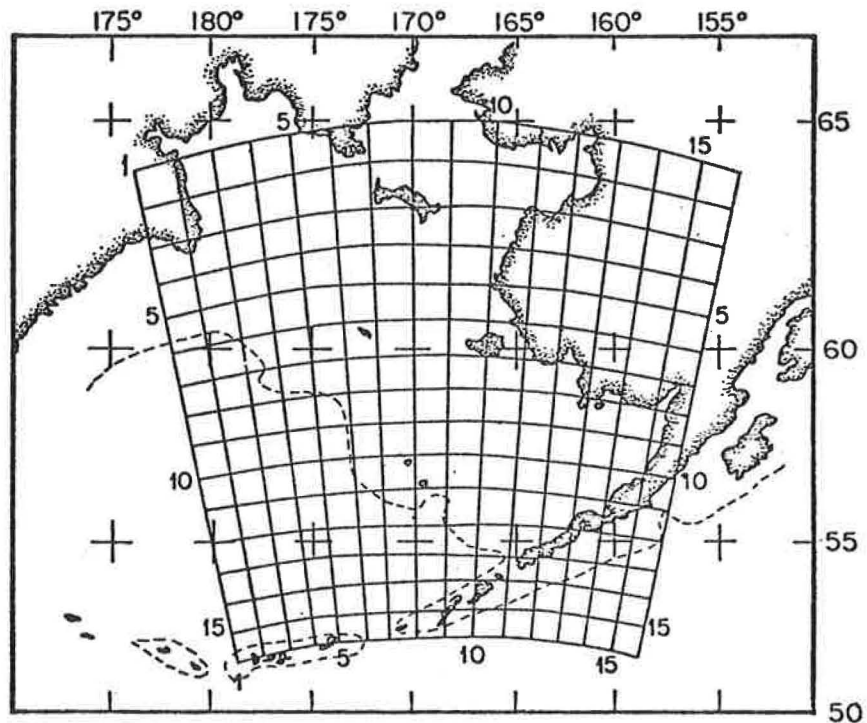


Figure 5.--DYNUMES III grid on Mercator projection.

### 3.1 Objectives and principles of ecosystem simulation

The overall objective of ecosystem simulation is to reproduce quantitatively all essential conditions and processes in the marine ecosystem in a time-dependent mode, based on all available pertinent data and knowledge. Among the applied objectives of this simulation are:

- Synthesis of all available information in reviewable manner.
- Determination of the magnitudes and present status of the marine living resources (stocks).

- Determine the effects of exploitation and environmental anomalies on these resources, thus to determine the fluctuations of the abundance and distribution of these resources in space and time.

There are some basic principles of ecosystem simulation, the fulfillment of which is essential for realistic simulation.

- The ecosystem simulation must include all components of the biota. This is necessary for realistic simulation of trophodynamic processes (feeding) and of processes dependent on feeding (such as growth). Due to computer core and time limitations, several species are often lumped into groups of ecologically similar species.
- The simulation must have a diagnostic phase (i.e. analysis of initial conditions) and a prognostic phase with proper time steps.
- The mathematical formulas in the simulation must serve for quantitative reproduction of known distributions and processes (i.e. to simulate the known and proven) rather than assuming that ecosystem or part of it behaves like a given mathematical formula.

### 3.2 Basic formulas used in NWAFC ecosystem models.

There are a great number of mathematical formulas used in an ecosystem simulation. Only a few basic formulas are presented in this summary. The most important of these formulas is the "biomass balance formula":

$$B_{i,t} = B_{i,t-1} (2-e^{-g}) e^{-m} - C_{i,t-1} \quad 5$$

where  $B_{i,t}$  is the biomass (e.g. in  $\text{kg}/\text{km}^2$ ) of species  $i$  in time step  $t$  and  $B_{i,t-1}$  is the same biomass in previous time step.  $C_{i,t-1}$  is predation loss (consumption) of species  $i$  in previous time step; its computation is laborious (see Formula 7).

The coefficients  $g$  and  $m$  are species and time step dependent. The growth coefficient- $g$  is determined empirically, considering the distribution of biomass with age, as growth is age dependent. Thus the variations in recruitment are reflected (and presented) in the variation of  $g$ . Furthermore, growth coefficient changes with temperature and with starvation. The mortality coefficient- $m$  includes spawning stress mortality and mortality from old age and diseases;  $f$  is a space and time dependent fishing intensity coefficient. The yield is computed as:

$$Y_{i,t} = B_{i,t} - B_{i,t} e^{-f} \quad 6$$

The consumption (predation) of species  $i$  ( $C_{i,t}$ ) is computed as a sum of predation of this species by all components of the ecosystem:

$$C_{i,t} = B_{i,t} q_i p_{i,i} + B_{j,t} q_j p_{i,j} + \dots + B_{n,t} q_n p_{i,n} \quad 7$$

where  $B_i$  to  $n$  are biomasses of species  $i$  to  $n$ ,  $q_i$  to  $n$  are food uptakes (requirements) of the individual species  $i$  to  $n$ --e.g. in terms of fractions of body weight daily and  $p_i$  to  $n$  are the fractions of species  $i$  in the food of species  $i$  to  $n$ . The food requirement  $q$  is in full models a function of temperature and food availability. The fraction of one species in the food of other species ( $p$ ) varies in space (from one grid point to another) and in time depending on the availability of suitable food.

It could be noted that predation ( $C$ ) has been included in "natural mortality" coefficient  $M$  in conventional single species models, whereas it is computed in detail in ecosystem models where it is also an age (size) dependent variable.

The age composition dependent growth rate is illustrated with Figures 6 and 7 and the age dependent total mortality in Pacific herring is shown on Figures 8a and 8b.

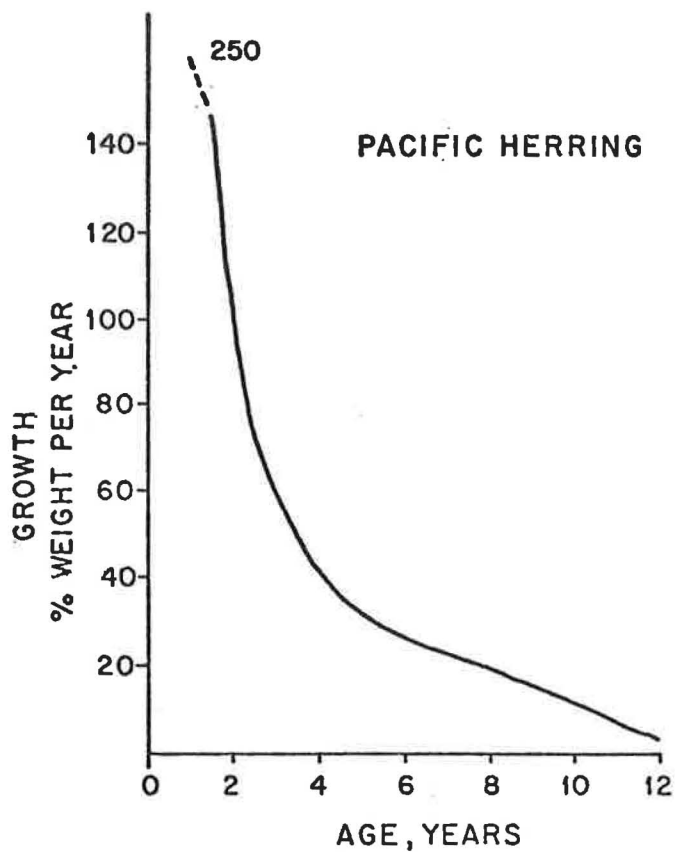


Figure 6. Growth of biomass (weight) of Pacific herring at different ages, as percent per year.

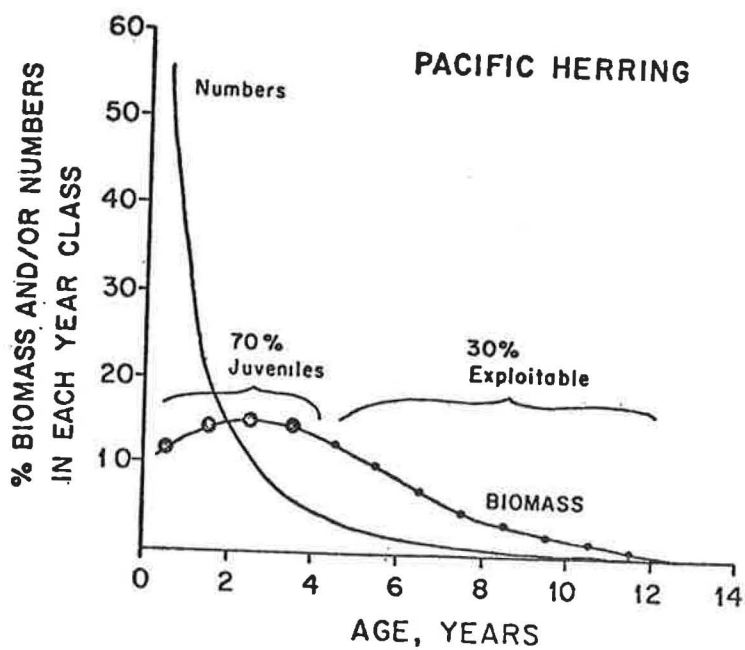


Figure 7. Distribution of biomass and numbers of Pacific herring within different year classes (% of total).

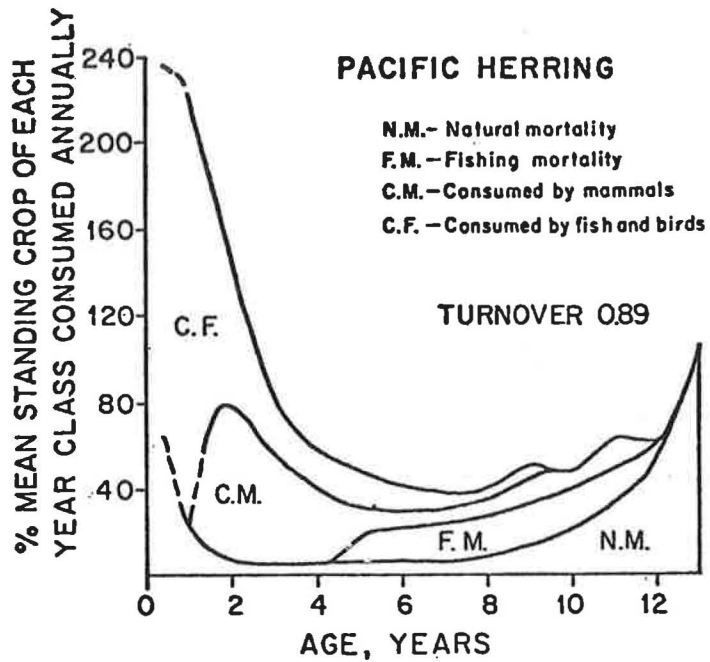


Figure 8a. Distribution of "consumption" (grazing, mortality, and fishery) with age of Pacific herring, as percent of mean standing crop of each year class.

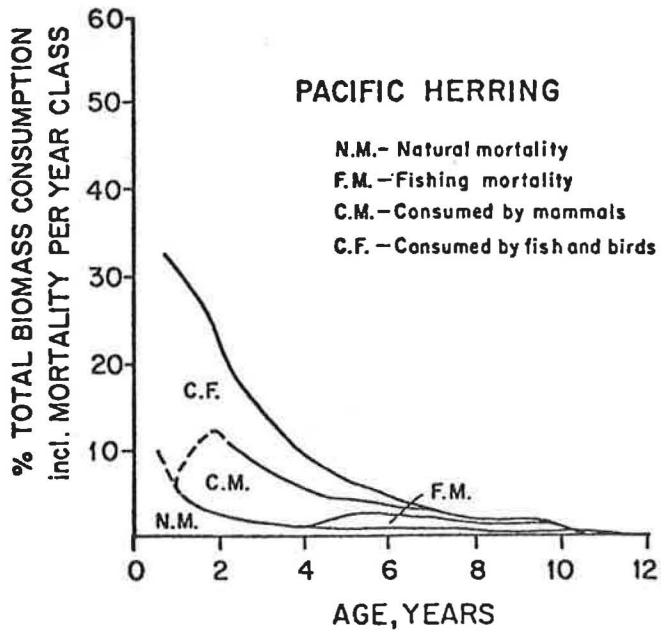


Figure 8b. Distribution of "consumption" with age of Pacific herring, as percent of total biomass.

The mortality of juvenile herring is high due to predation. It reaches a minimum before the maturation and about at the size and age when herring would become fully recruited for trawl fishery. After the year when about 80% of the population has reached maturity, the mortality increases about ten percent per year. This mortality can be considered spawning stress mortality, although part of it might be due to decreased vulnerability to gear in older fish.

4. Determination of equilibrium biomasses in the eastern Bering Sea.

The real magnitudes of the biomasses in the Bering Sea are at present ill known from hereto conventional approaches. This situation is caused by many circumstances such as difficulties in estimating vulnerability and availability (in total the catchability) coefficients necessary for conversion of trawling survey results; extensive seasonal migrations of species; large area with respect to survey and research effort available; near absence of sonar and pelagic trawl surveys; presence of high quantity of marine mammals as apex predators; and underutilization of most species and short full exploitation period of others.

As most species are quantitatively related to each other by predation, we can determine the quantitative relations by species if we know their food requirements and food composition. Furthermore, we can find some species in a given region (e.g. pollock, yellowfin sole, etc.) whose biomass level is better known and/or whose consumption (predation) by mammals and/or fishery can be determined with reasonable accuracy. Thus we can use the formulas 5 to 7 to determine a unique solution under defined conditions (i.e. one known biomass and prescribed (known) food requirements and composition of food). This has been done in NWAFC for the eastern Bering Sea. The results are given in Table 1.



Table 1.--Minimum in ecosystem sustainable biomasses (equilibrium biomasses) in thousand tons in the eastern Bering Sea as computed with PROBUB model; percent exploitable biomass and catchability factors for survey trawl.

Species/group of species	Equilibrium biomasses	Percent exploitable	Catchability factor
<u>Demersal</u>			
Greenland turbot, halibut	513	54	0.68
Flathead sole, arrowtooth flounder	689	45	0.68
Yellowfin and rock sole, Alaska plaice	1,676	45	0.72
Other flatfish	1,139	28	0.53
Elasmobranches, cottids	(4,091)	-?	0.28
<u>Semi-demersal</u>			
Pollock	9,206	70	0.42
Cod	1,074	72	0.36
Sablefish	(190)	40	0.15
Rockfish	1,813	30	0.20
<u>Pelagic</u>			
Herring	2,113	30	0.08
Capelin, other smelt	(5,000)	-?	0.03
Sand lance	(3,500)	-	<0.03
<u>Varia</u>			
Atka mackerel, + macrurids	1,553	45	0.06
Squid	(2,500)	-?	<0.02
Crab	993	40	0.21
Shrimp	(1,485)	65	<0.04

The equilibrium biomasses given in Table 1 must be considered minimum biomasses sustainable in the given ecosystem. The "minimum" is achieved by specifying highest plausible biomass growth rates and lowest plausible food requirements (e.g. in terms of percent of body weight daily). Both parameters can be estimated from available empirical data. Experiences show that people concerned with management would like to see conservative estimates--thus another reason to present minimum, in ecosystem sustainable biomasses.

Some limits of accuracy of the computed biomasses can be obtained by considering the reliability and accuracy of input data and making repeated computer runs with different plausible inputs. In general the error is about  $\pm 30\%$ , varying from species to species.

After obtaining the equilibrium biomasses, various experiments can be carried out with the PROBUB model in prognostic mode. These experiments can include the study of the effects of environmental anomalies and--most importantly for management--the determination of the effects of varying fishery on the resources.

The gridded model DYNUMES provides more details, especially in respect to spatial distribution, allowing the computation of the effects of different spatial distribution of predator and prey.

5. Verification and validation of the model and the use of exploratory and commercial fisheries data.

Results from any model computations are only as good as the inputs (data used) and as correct as the formulations in it which describe and reproduce the system. Verification refers to the latter aspect of the models. It is done by professional peers and others fully experienced and knowledgeable. A small, international workshop on fisheries ecosystem models was recently concluded in Seattle which went through in detail the NWAFC ecosystem models. The validation of the model results is carried out by independent, pertinent data collection. There is a continuous need to improve the data input in any complex ecosystem model.

The validation of the ecosystem simulation in the Bering Sea can be made with NWAFC's trawling survey data. The survey data must be converted to exploitable biomass, using species specific gear vulnerability and areal and seasonal availability coefficients. Direct observational data on gear vulnerability and availability are usually not available, thus indirect estimates must be used, based on a variety of considerations and indirect observations.

In Table 2 a comparison of exploitable biomasses as obtained from surveys (adjusted with vulnerability and availability coefficients) is made with the exploitable biomasses obtained from PROBUB model. A detailed analyses of this comparison is given elsewhere (Granfelt, in prep.). It has been concluded in general that the PROBUB model results are more realistic and accurate than the survey results; however, the use of the model costs only a very small fraction of the cost of the surveys.

Table 2.--Comparison of exploitable biomasses as obtained by surveys, reported in management plans, and computed with PROBUB model. Eastern Bering Sea.

(in 1,000 metric tons)				
Species/group of species	Mean, 1975, 1976 surveys (converted, see Table 4)	Groundfish management plan	Minimum sustainable exploitable biomass from PROBUB model	MSY from management plan
<u>Demersal</u>				
Greenland turbot, halibut	176	?	277	105
Flathead sole, arrowtooth flounder	206	94-132	310	
Yellowfin and rock sole, Alaska plaice	2,716	992 + 149 (232-334)	754	169-260
Other flatfish			319	44-77
Elasmobranchs, cottids			(2,864)	
<u>Semi-demersal</u>				
Pollock	3,698	?	6,444	1,100-1,600
Cod	233	?	773	59
Sablefish		?	(76)	11
Rockfish		?	544	75
<u>Pelagic</u>				
Herring			634	
Capelin, other smelt			(1,500)	
Sand lance				
<u>Varia</u>				
Atka mackerel, + macrurids		?	699	33
Squid			(1,000)	
Crab			397	
Shrimp			965	

The statements above should not be interpreted that exploratory fishery surveys are no longer necessary. Rather, it is suggested that the surveys be complimented with ecosystem models and that the emphasis of the surveys be shifted to prefishery juveniles (i.e. emphasis on sonar and pelagic surveys). Furthermore, as good trophic data on fish (stomach analyses) are scarce from the Bering Sea, it is suggested that future surveys include this subject (i.e. quantitative analyses of food composition by size of predator and prey).

The areal surveys on spawning herring and capelin by ADFG has recently provided valuable data on the resources of these species, and it is desirable that these surveys continue.

After introduction of quotas, most of the observations and data collections from commercial fleets have lost much of their value for resource assessment. For example, the CPU from commercial vessels has become quasi-useless. The properly collected length and age frequency data are still useful for estimation of the present state of exploitable biomasses. Unfortunately these data cannot be used successfully for cohort (virtual population) analyses in regulated (with quotas) and underexploited fisheries.

The ecosystem simulation models can be used as guides to design experiments which can be validated either with exploratory fishery surveys or with specific data from commercial fisheries.

#### 6. The use of ecosystem simulation models in fisheries management.

The ecosystem simulation models are used in prognostic mode to evaluate the effects of fishery in temporal as well as in spatial aspects, by changing fishing intensity coefficient (input) in desired level in desired locations, and studying the resulting changes in the target species as well as in species indirectly affected by the fishery through trophic (food) relations.

In the past little attention has been given to the fact that biomass of any given species declines faster (nonlinearly) with increased fishing effort than simple annual linear computations would indicate. This decline is shown on Figure 9 using biomass balance formula (5) and yield formula (6) with heavier fishery in the early spring months. The difference in yield in three years is  $411 \text{ kg/km}^2$ , whereas the biomass has declined  $1,150 \text{ kg/km}^2$  more in the heavier fished case in three years.

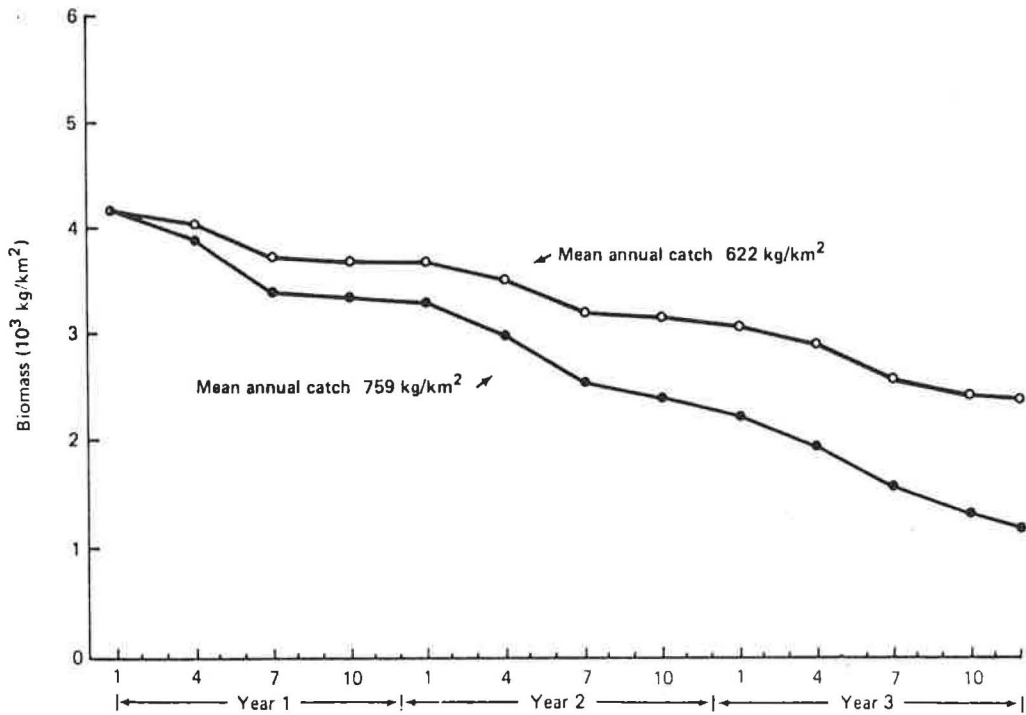


Figure 9 Decrease of biomass with two different annual yields (formulas 5 and 6)

The ecosystem model DYNUMES has been used among others to study the effects of variation of squid stocks from year to year on herring stocks and the possible effects of the control of the herds of beasts on herring (Laevastu and Favorite 1978). The same study explored quantitatively the effects of surface temperature anomalies on the growth of herring biomass. Examples of this study are given in Figures 10 and 11 in form of spatial distribution of sources (biomass growth exceeds predation and mortality) and sinks (predation and mortality exceeds biomass growth).

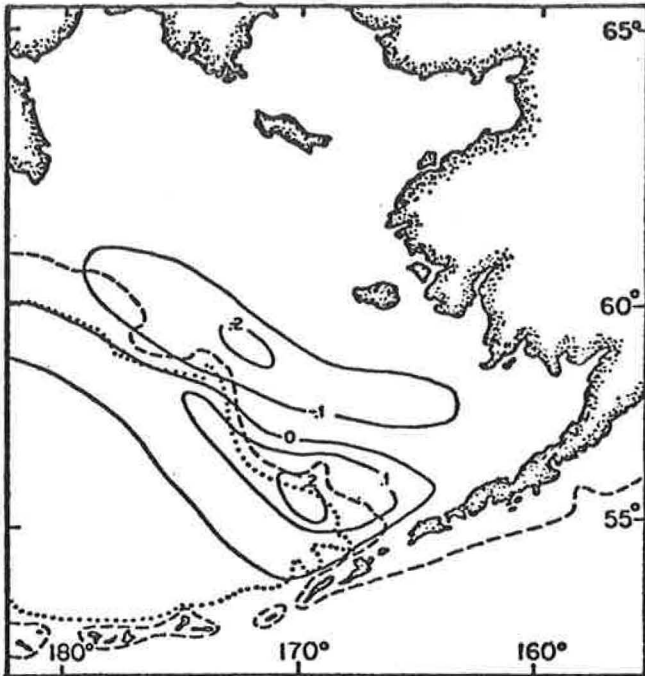


Figure 10.--Herring sources and sinks in tons/km<sup>2</sup>, February.

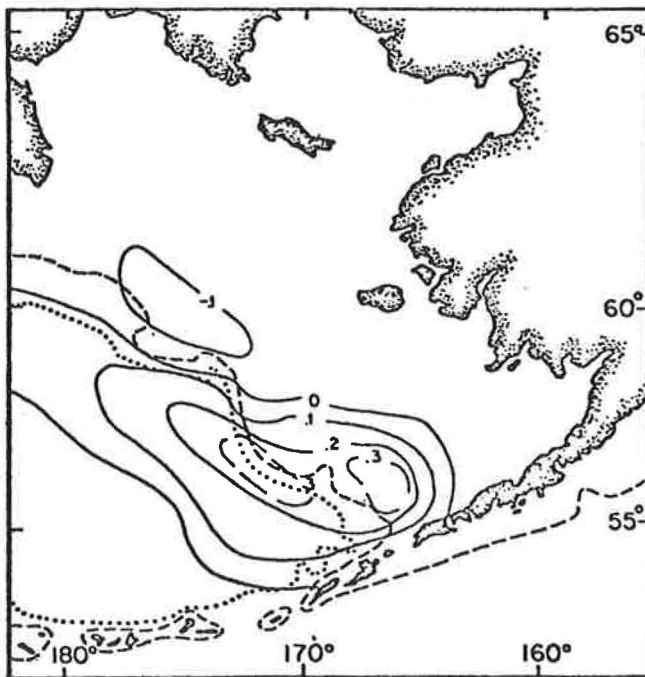


Figure 11.--Herring sources and sinks in tons/km<sup>2</sup> in February (1.5°C positive anomaly).

The prediction of larval and juvenile stages is still largely an unsolved problem in fisheries. Some inclusions on the larval survival might be drawn from ecosystem models, but validation of these inclusions takes time.

The use of the ecosystem approach allows us to bypass some fables in the fisheries science and to show that there is no Utopia in fisheries either--i.e. no MSY in the stricter definitions. The ecosystem simulations show what we lose (take) from one species might be compensated in other species. Furthermore, the "natural mortality" is no more a fable in ecosystem models as a great part of it--i.e. the age (size) dependent predation mortality is determined in considerable detail. The spawning stress mortality has also found some solution (Alverson and Granfeldt, MS).

Thus, lately it has become more obvious that the fish stocks can no longer be managed on a species by species "piecemeal" fashion, but together as an ecosystem where one influences the other and decline of one might induce the decline of other species.

The role of fisheries science in fisheries management and policy has lately become also better defined: it is the duty of scientists to determine the size of the stocks, their distributions, fluctuations caused by multitude of factors, and their response to present and prospective exploitation.

It is up to the representatives of the public and appointed or elected managers to determine (with the advice of economists) which fish to harvest and in which manner, e.g. should man harvest heavily the gadoids (pollock and cod) relieving at the same time predation pressure on herring and harvest also herring in higher quantities as a consequence, harvest only herring roe to the extent that recruitment would not suffer greatly or harvest only little or nothing, leaving the beast to control the food resources of the sea.

Finally, it could be pointed out that the ecosystem approach in fisheries did not develop as a national project, nor as a project originating from basic research in the universities or as a request from managers, but rather as a result of foresight, understanding, and wisdom of some laboratory directors and their division and task leaders. Considerably more input and development is needed to finalize the extensive simulation models and, above all, effort and time is needed to explain these models to professional peers as well as to managers and other users. After all it took over twenty years to explain and propagate the single species approach.



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