This paper not to be cited without prior reference to the authors

International Council for the Exploration of the Sea

C.M. 1980/J:15
Baltic Fish Committee

USE OF A MULTI-SPECIES MODEL TO ASSESS BALTIC STOCKS AND FORECAST CATCHES

by

Jan Horbowy and Michał Kuptel

Sea Fisheries Institute
Al.Zjednoczenia 1,
81-345 Gdynia, Poland.

Abstract

In the present paper, a multi-species stock assessment model (Danish model) was used to assess the abundance of fish (herring, sprat and cod) in the Baltic. A forecast of the biomass and catches of the basic species for 1980-1985, has also been given.

1. Introduction.

It is expected that multi-species models will play a significant role in the assessment of stock abundance in the near future. This was illustrated at the Statutory Meeting (No.67) of ICES which took place in Warsaw in 1979, with the setting up of a working group to determine the data required to apply multi-species models and work out and international research programme for the purpose of supplying these data. Work on multi-species models was commenced by Riffenburgh (1969) and a group of Danish scientists headed by K.P.Andersen and E.Ursin (1973, 1977). The present paper constitutes an attempt to apply the "Danish model" to symulate the abundance of Baltic fish stocks. In Poland, such work has already been undertaken with success by W.Mandecki (1976) and J.Majkowski (1977).

2. Mathematical Description of the Model

The following system of differential equations (Danish model) was adopted to assess the abundance of stocks and forecast the catches of the three main species of Baltic fish (cod, herring and sprat):

$$\frac{dN_i}{dt} = -(F_i+M1_i+M2_i)N_i \,,$$

$$\frac{dw_i}{dt} = v_i h_i f_i w_i^{2/3} - K_i w_i \,, \qquad (1)$$

$$\frac{dY_i}{dt} = F_i N_i w_i$$

where:

$$f_i = \frac{\varphi_i}{\varphi_i+Q_i}$$

$$M2_i = \sum_j h_j w_j^{2/3} N_j G_{ji} / (\varphi_j + Q_j)$$

$$\varphi_i = \sum_j G_{ij} N_j w_j$$

$$G_{ij} = \rho_{ij} \exp\left(-\frac{1}{2\sigma_i^2}(\ln w_i/w_j - \eta_i)^2\right)$$

the symbols used denote:

n = number of entities (an entity is one age group of one species)

N_i = number of individuals in entity i

w_i = body weight of individual in entity i

Y_i = accumulated yield of entity i

F_i = instantaneous coefficient of fishing mortality of entity i

$M1_i$ = instantaneous natural mortality coefficient (not due to predation) of entity i

$M2_i$ = instantaneous natural mortality coefficient of entity i due to predation

f_i = feeding level of entity i

v_i, h_i, K_i = parameters of growth equation of entity i.
The remaining variables and parameters have the same meaning as given by K.P.Anderson and E.Ursin (1977).

Then assuming constancy of coefficients $M2_i$ and f_i, each of equations (1) was solved analytically and the system of equations (2) was obtained:

$$
\begin{aligned}
&N_i/t+\Delta t/=N_i/t/\exp\left(-(M1_i+M2_i+F_i)\Delta t\right),\\
&w_i/t+\Delta t/=\left[v_ih_if_i/K_i+\left(w_i/t/^{1/3}-v_ih_if_i/K_i\right)\exp\left(-K_i\Delta t/3\right)\right]^3,\\
&\Delta Y_i/t/=F_iN_i/t/\sum_{l=0}^{3}A_lB_i^{3-l}\left(w_i/t/-B_i\right)^l/C_{il}\left(1-\exp\left(-C_{il}\Delta t\right)\right)
\end{aligned}
\qquad (2)
$$

where A_l=1,3,3,1, $B_i=v_ih_if_i/K_i$, $C_{il}=M1_i+M2_i+F_i+lK_i/3$.

Using the assumed initial values N_i^o and w_i^o, the above system of equations was solved on an Odra 1305 computer with a 1/12 year step over the years 1974-1979, the existing values of coefficients $M2_i$ and f_i being calculated first each time. This process is interrupted by spawning, which is here instantaneous ("momentaneous"). At that moment, the particular entities advance to the consecutive, older age group, losing - if they participate in reproduction - part p_i of their weight. The last age group is the global group, its numbers are calculated by adding the numerical value of the penultimate age group, whereas the weight is the weighted average of the last and penultimate age group. Age group I is introduced to the model as an external variable (number of fish and weight of a single individual); the application of stock-recruitment relationship and modelling of the abundance of 0 age group was waived here. After spawning, calculation according to equations (2) are continued.

Zooplankton and benthos are also included in the model.

These are external variables - each month their new numbers are introduced to the model, the weight of a single individual remains constant.

3. The Application of the Model to Symulate the Abundance of Baltic Stocks

The model discussed in part 2 was applied in the area of the Baltic Proper, in sub-regions 24-29S. According to the division of cod (a predator) by ICES into the stock of sub-region 24 and that of sub-regions 25-29S, herring and sprat (prey) were analogically divided. The latter, however, are divided by ICES into herring stocks from sub-regions 22-24, those from sub-regions 25-27 and from sub-regions 28-29S, sprat from sub-regions 22, 24, 25, sprat from sub-regions 26, 28 and those from sub-regions 27, 29, 32. Basing on the reports of the Baltic Ground and Pelagic Fishes Working Group (ICES 1980), the following data and parameters were worked out for the stock newly established for the needs of the model (herring from sub-region 24, herring from sub-regions 25-29S, sprat from sub-region 24 and that from sub-regions 25-29S):

a) abundance as on 1st January 1974 - from the VPA, adding, or breaking down according to catches from particular sub-regions, the numbers in the "old" stocks,
b) the numbers in age-group I in 1974-1979 - calculating as above,
c) coefficients of mean fishing mortalities in the years 1974-79 - if the newly-created stock is the sum of the "old" stocks, its fishing mortality is calculated as the mean fishing mortality of the "old" stocks weighted by the numbers in these stocks,
d) mean weight in age groups - calculated as above.

The model consists of six fish stocks (cod, herring and sprat from sub-region 24, cod, herring and sprat from sub-regions 25-29S) and 4 non-fish "species", each consisting of one age group (zooplankton and benthos from sub-region 24, zooplankton and benthos from sub-regions 25-29S). These constitute together, 49 age groups (entities):

- sprat	from	sub-region	24	- 5	age groups,	i = 1,2,..,5
- "	"	"	25-29S	- 9	age groups,	i = 6,...,14
- herring	"	"	24	- 6	" "	, i = 15,.., 20
- "	"	"	25-29S	-11	" "	, i = 21,.., 31
- cod	"	"	24	- 5	" "	, i = 32,.., 36
- "	"	"	25-29S	- 9	" "	, i = 37,.., 45
- zooplankton	"	"	24	- 1	" "	, i = 46
- "	"	"	25-29S	- 1	" "	, i = 47
- benthos	"	"	24	- 1	" "	, i = 48
- "	"	"	25-29S	- 1	" "	, i = 49

In the model, both stocks of sprat feed on zooplankton from their sub-regions and the herring stocks - on zooplankton and to a lesser extent, benthos, from their sub-regions. The cod in sub-region 24 feeds on herring, sprats, young cod, zooplankton and benthos from their sub-region, also (to a lesser extent) feeding on herring, sprat, zooplankton and benthos from sub-regions 25-29S. The cod in sub-regions 25-29S feed on herring, sprat, young cod, zooplankton and benthos from these sub-regions only. The model gives herring and cod spawning as each year on 1st May, whilst that of the sprat - 1st June. Due to the difficulties in obtaining suitable results, the drop in body weight of cod from sub-regions 25-29S during spawning (p_i = 0, i = 27, ...45) has not been modelled.

The data obtained according to the description in a) and d) were applied as the first approximation of number and weight of fish when the model was started (1st January, 1974).

Similarly, the data from b) and c) were taken as the first approximation of recruitment to age group I and coefficients of fishing mortality in the years 1974-1979.

As mentioned in section 2, the zooplankton and benthos consumed by the fish is introduced to the model as an external variable on the 1st of each month. Their numbers in each month of a given year are found on the basis of annual production (Thurow 1978), divided by the mean weight of the individual and broken down into particular months according to the distribution of the zooplankton and benthos biomass over the period of one year in the Gulf of Gdańsk. The annual production was found from the mean production over a period of several years and broken down into annual production according to the distribution of zooplankton and benthos biomass in consecutive years, in the Gulf of Gdańsk.

The mean weight of zooplankton and benthos was so chosen that their consumption by the fish in the model was comparable with the consumption defined by Załachowski (1976).

Such unknown parameters as $\eta, \gamma, Q, M1, \varsigma, P$ were so adjusted as to ensure that the model gave results which conformed, as close as possible, with reality. Where necessary, the numbers and starting weight of fish, recruitment to age group I, and even - in the case of cod from sub-regions 25-29S - coefficients of fishing mortality, were similarly adjusted.

The conformity of catches recorded by statistics with those calculated in the model (Figs. 1,2, Table 1), and analogical conformity of mean weights in age groups, were mainly assumed as the criterion of the conformity of the model with reality.

As can be seen, the conformity is quite good, although it should be mentioned that it has only been managed to carry out a few runs of the model. The only greater differences occur in the case of sprat from sub-region 24.

This is most probably due to lack of knowledge of the exact catches in this zone (Danish catches are given for sub-regions 24 and 25 together). It is also possible that fluctuations in fishing effort in sub-region 24 differ from those in sub-regions 22, 24 and 25 as a whole (this would means that the coefficients of fishing mortality for sprat from region 24 would be inadequate). Apart from this, the coefficients of partial recruitment are constant in consecutive years, for a given species, which also might result in errors of several percent in the catch calculated in the model.

4. Predictions of the Biomass and Catches of Cod, Herring and Sprat from Sub-regions 24-29S in the Years 1980-85

The prediction of the biomass and catches of cod, herring and sprat in sub-regions 24 and 25-29S in the years 1980-1985 was based on the model under discussion. The figures obtained during the final step of running the model for 1974-79 were assumed as the initial values for the numbers and body weights of the particular entities on 1st January 1980. The prediction was carried out in three variants (Table 7). In each of these, the assumed fishing mortality values for both stocks of herring and sprat, also the numbers in age group I of both stocks of cod, herring and sprat are invariable. What do vary, are the values of the fishing mortality coefficients for cod. It was assumed that:

1) herring
   a) the numbers in age group I for the years 1980-85 will be equal to the arithmetic mean of age group I in the years 1974-79
   b) the fishing mortality coefficients for the years 1980-85 will be equal to the arithmetic mean of fishing mortality coefficients in the years 1974-79.
2) sprat
   a) the numbers in age group I for the years 1981-85 will be equal to the arithmetic mean of age group I in the years 1974-79, and will be 30% less than the mean in 1980.
   b) the fishing mortality coefficients for the stock in sub-region 24 will remain at the 1979 level (F = 0.26); those for the stock in sub-regions 25-29S will remain at the 1979 level (F = 0.32) in the years 1980-1982, and increase to 0.5 in the years 1983-85.
3) cod
   a) the numbers in age group I in the years 1980-85 will constitute 115, 110, 85, 95, 100 and 100% of the mean for the years 1970-77, respectively,
   b) in variant I, the fishing mortality coefficients will be equal to those of 1979, in variants II and III they will be 20% higher and 20% lower than the 1979 level, respectively.

The results of the predictions of stock biomasses and catches are shown in Figs. 1, 2, 3, 4 and summarized in Tables 6 and 8. Taking yield into account, fishery variant II would appear to be best, but its effect on cod recruitment is not considered.

The following conclusions can therefore be drawn:

a) there is a strong relationship between the biomass of cod (predator) and herring and sprat (prey),

b) the youngest age groups of prey have the highest predation mortality,

c) the amount of food available for the cod drops as the result of a decrease in the biomass of herring and sprat,

d) age groups I of herring and sprat are much more abundant than those calculated from the VPA.

We would like to express our thanks to our colleagues Dr. J.Elwertowski, Dr. J.Netzel, Dr.M.Kosior and Dr.K. Strzyżewska for both consultations and supplying some of the data.

References.

Andersen K.P. and Ursin E., 1977, A multispecies extension to the Beverton and Holt theory of fishing with accounts of phosphorus circulation and primery production, Meddr. Danm. Fisk.-og Havunders. N.S. 7:319-435.

Majkowski J., 1977, Prognosis for catches of cod, herring and sprat in the Baltic Sea, and their optimization with the aid of mathematical model, Pol. Arch. Hydrobiol. 3:361-382.

Mandecki W., 1976, A computer simulation model for interacting fish population studies, applied to the Baltic, Pol. Arch. Hydrobiol. 2: 281-307.

Netzel J., 1976, Wędrówki dorsza bałtyckiego i próba określenia dynamiki jego populacji wna podstawie znakowań w latach 1954-63, Studia i Materiały, seria B, nr 37,

Thurow F.R., 1978, The fish resources of the Baltic Sea, FAO Fisheries Circular No. 708,

Załachowski W., Szypuła J., Krzykawski S. and Krzykawska I., Composition and amount of food consumed by sprat, herring and cod in the Southern Baltic in the years 1971-1974, ICES, C.M.1976/P:23.

Anon., 1980, Report of the Working Group on assessment of demersal stocks in the Baltic, C.M.1980/J:3.

Anon., 1980, Report of the Working Group on assessment of pelagic stocks in the Baltic, C.M.1980/J:4.

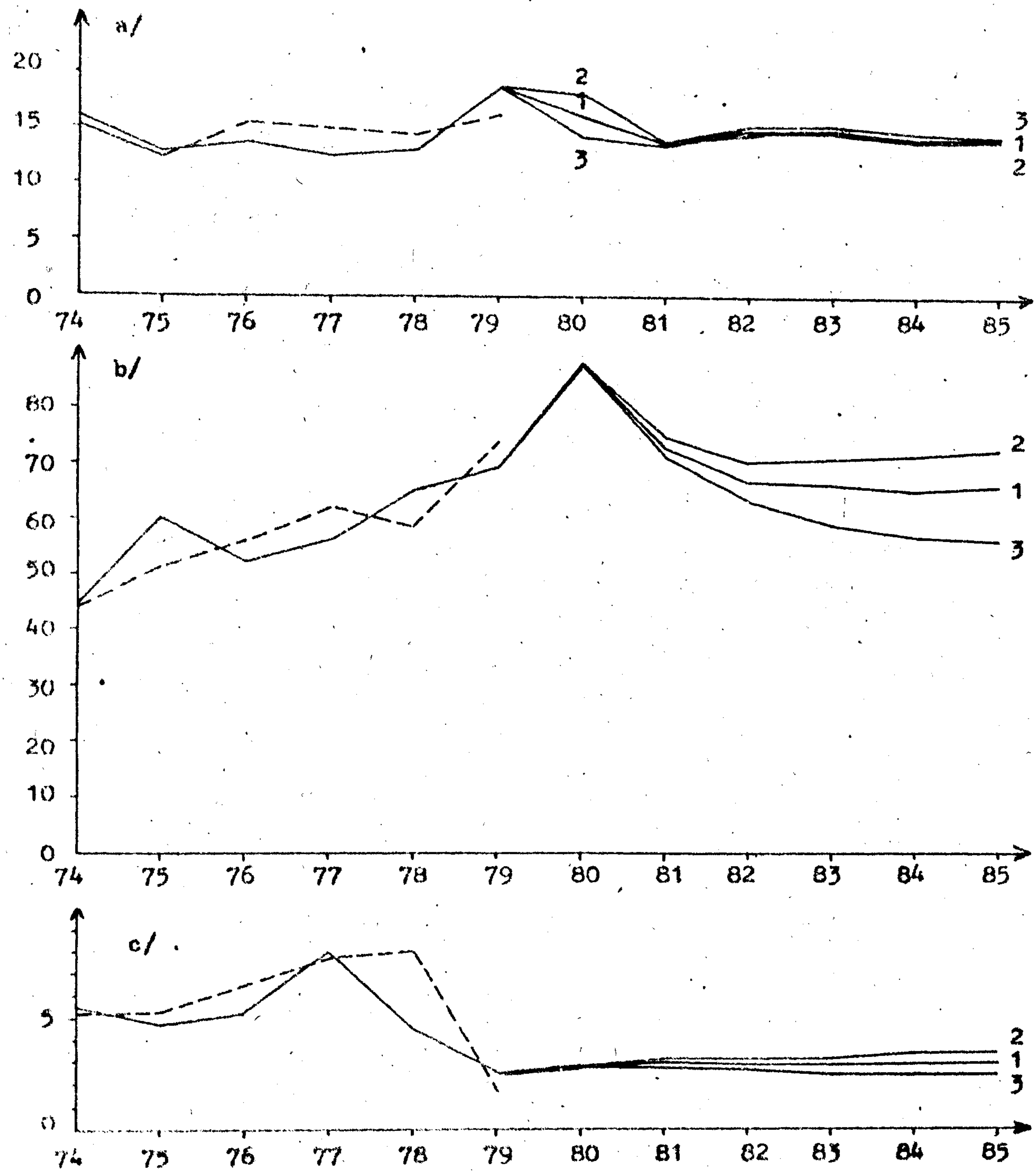

FIGURE 1. Observed and calculated catches of cod /a/, herring /b/ and sprat /c/ in 1974-79 years and catch prediction for 1980-85 y. in sub-division 24 /three variants of cod fishery for prediction /.

— — — — observed values

———— calculated values

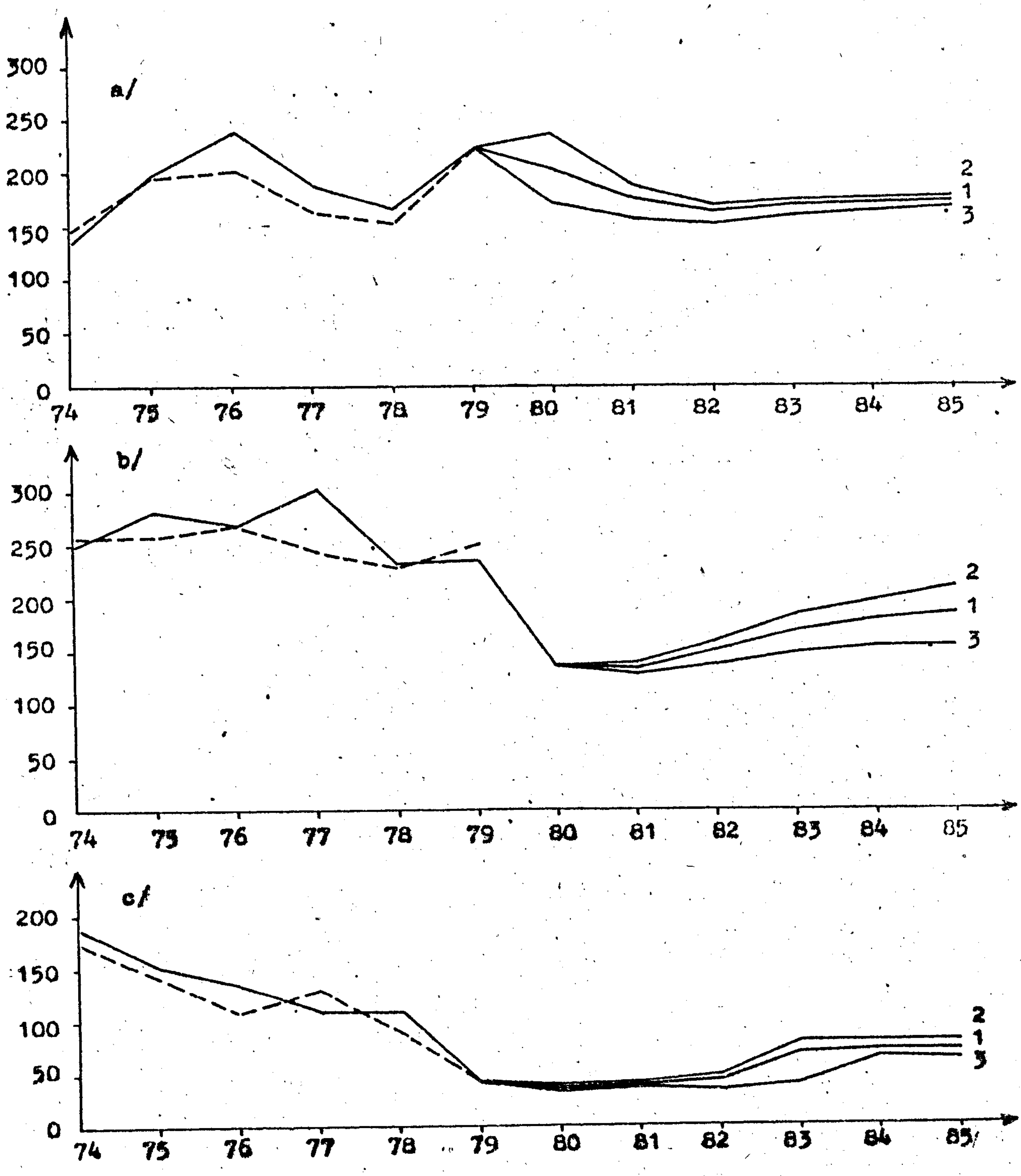

FIGURE 2. Observed and calculated catches of cod /a/, herring /b/ and sprat /c/in 1974-79 y and catch prediction for 1980-85 y in sub-divisions 25-29S /three variants of cod fishery for prediction/.

— — — — observed values
———— calculated values

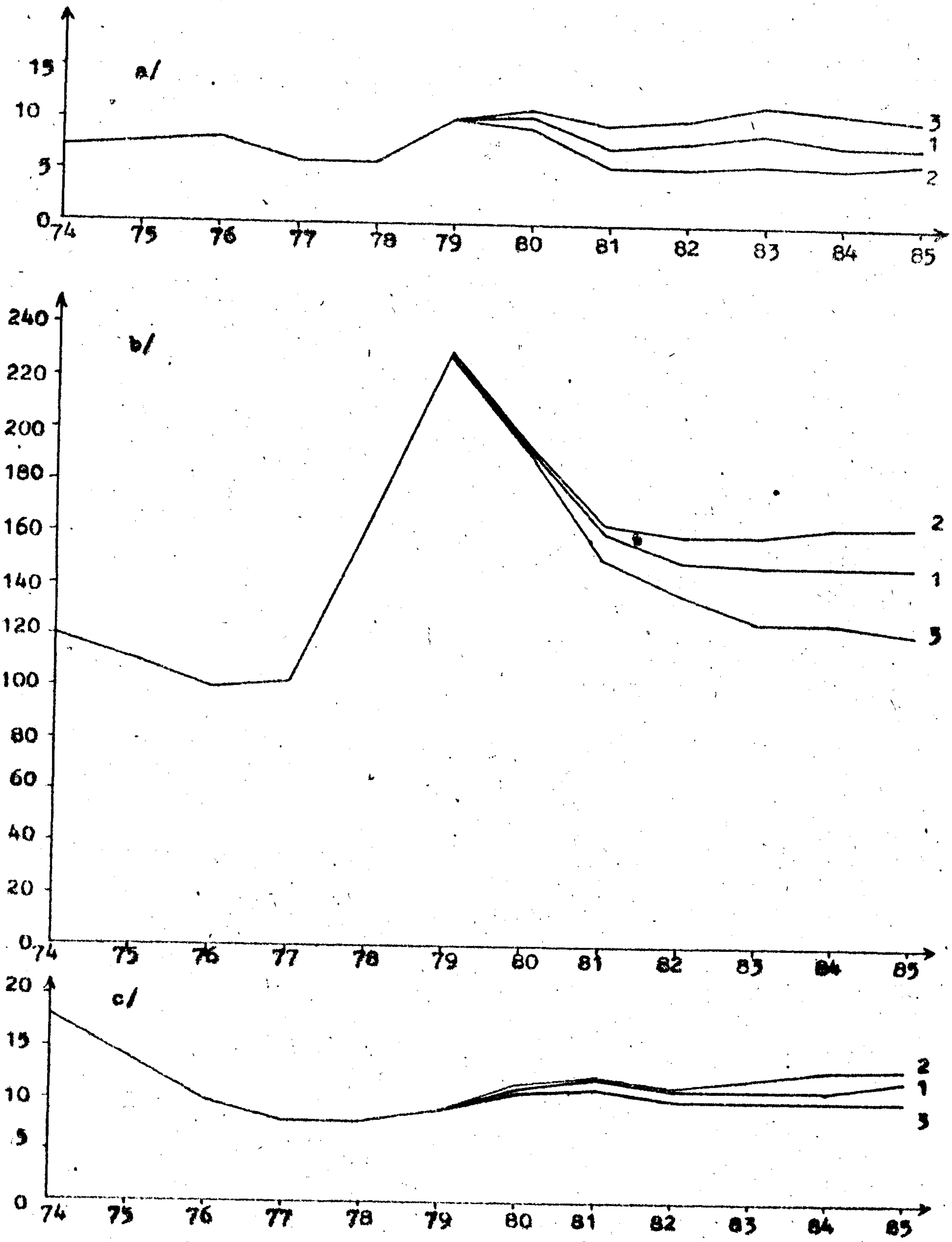

FIGURE 3. Calculated spawning stock biomass for 1974-79y and prediction for 1980-85y /three variants of fishery/.in sub-division 24.

a/ cod
b/ herring
c/ sprat

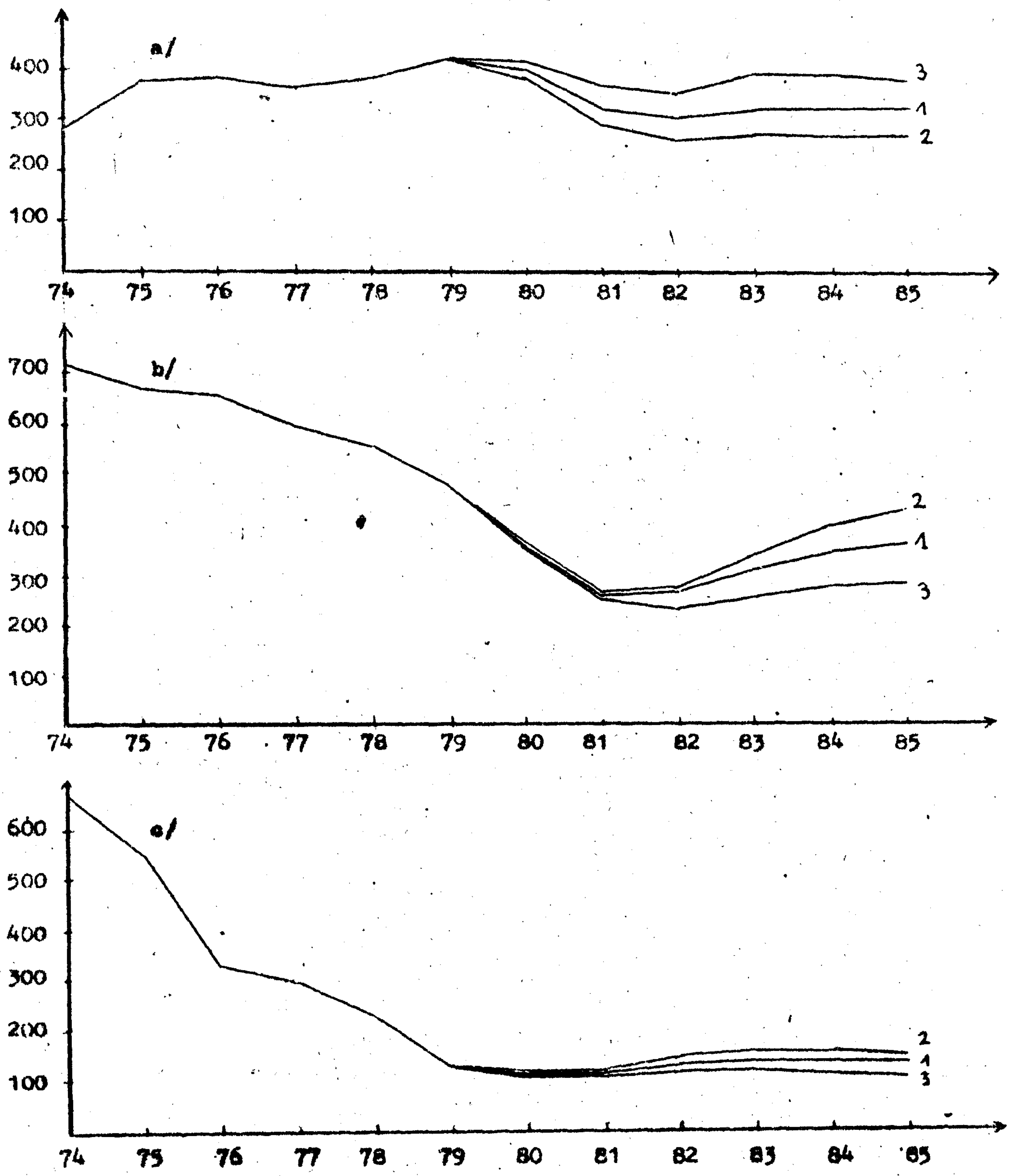

FIGURE 4. Calculated spawning stock biomass for 1974–79y and prediction for 1980–85y /three variants of fishery/ in sub-divisions 25–29S

a/ cod
b/ herring
c/ sprat

A/

stock \ year	74		75		76		77		78		79	
	obs	calc	obs	calc	obs	calc	obs	calc	obs	calc	obs	calc
cod 24	15.2	16.0	12.5	12.9	15.4	13.7	15.1	12.4	14.6	13.0	16.3	19.0
cod 25-29S	147.8	132.7	194.6	199.7	203.3	240.8	164.7	189.3	154.0	167.5	222.3	224.1
herring 24	43.6	44.3	51.4	60.4	56.3	52.2	62.1	56.2	59.1	65.3	74.0	69.3
herring 25-29S	257.3	247.9	259.0	282.1	270.1	269.7	244.0	301.9	230.3	233.9	252.5	237.0
sprat 24	5.2	5.5	5.3	4.8	6.5	5.2	7.7	7.9	8.1	4.4	1.7	2.5
sprat 25-29S	174.7	186.8	143.3	152.5	110.2	134.6	131.4	113.3	89.6	110.3	45.6	45.4

B/

stock \ year	74	75	76	77	78	79
cod 24	-4.9	-2.8	10.7	17.6	10.9	-16.6
cod 25-29S	10.2	-2.6	-18.4	-14.9	-8.8	-0.1
herring 24	-1.7	-17.4	7.2	9.6	-10.6	6.4
herring 25-29S	3.6	-8.9	0.2	-23.7	-1.5	6.2
sprat24	-5.6	8.8	20.3	-3.3	45.5	-48.6
sprat 25-29S	-6.9	-6.4	-22.2	13.8	-23.0	0.1
mean x/	6.2	7.5	12.5	20.0	8.7	4.8

TABLE 1. A/ Calculated and observed values of catches of cod, herring and sprat in sub-divisions 24 and 25-29S in 1974-79 years. / thousands of tons/.

B/ Relative error of calculated values. /per-cent/.

x/ calculated from formula $\text{mean} = \sqrt{\frac{\sum (C_k - \bar{C}_k)^2}{\sum C_k^2}}$, where C_k, $\bar{C}_k$ are observed and calculated values.

A/

age-group / stock	1	2	3	4	5	6	7	8	9	10	11
cod 24	25	13	3	1	0.4						
cod 25-29S	620	400	170	60	16	5	2	1	0.5		
herring 24	787	389	399	279	98	36					
herring 25-29S	7382	3800	2674	2312	1675	890	1394	109	112	80	46
sprat 24	654	727	267	177	163						
sprat 25-29S	47000	34000	14000	5300	4200	1600	1600	100	130		

B/

year / stock	74	75	76	77	78	79
cod 24	29	22	23	45	33	19
cod 25-29S	506	471	694	1053	754	263
herring 24	1461	1453	1768	4135	2974	836
herring 25-29S	13800	10100	14300	10900	6700	2600
sprat 24	654	282	1113	797	1040	1023
sprat 25-29S	30800	9200	49600	24300	8300	27000

TABLE 2. A/ Starting values of numbers /1.01.1974/ /millions of fish/.

B/ I-age group size in numbers /"recruitment"/ /millions of fish/.

stock	η	$\gamma = \frac{1}{2\sigma^2}$	M1	h	k	Q $[10^3 g]$	v
cod 24	4.605	.173	.2	46.83	.88	45000000	.48
cod 25-29S	4.605	.173	.25	22.93	.21	450000000	.48
herring 24	5.9	.04	.15	26.25	1.28	87000000	.48
herring 25-29S	5.9	.02	.05	11.91	.58	810000000	.48
sprat 24	5.6	.15	.05	9.86	1.32	17000000	.48
sprat 25-29S	5.6	.15	.05	8.07	1.15	170000000	.48

TABLE 3. Parameter values.

prey / predator	cod 24	cod 25-29	herring 24	herring 25-29S	sprat 24	sprat 25-29S	zoopl. 24	zoopl. 25-29S	benthos 24	benthos 25-29S
cod 24	.4	0	1	.02	.65	.02	1	.02	1	.01
cod 25-29S	0	.2	0	.7	0	.5	0	1	0	1
herring 24	0	0	0	0	0	0	1	0	1	0
herring 25-29S	0	0	0	0	0	0	0	1	0	1
sprat 24	0	0	0	0	0	0	1	0	0	0
sprat 25-29S	0	0	0	0	0	0	0	1	0	0

TABLE 4. Vulnerability indices.

year / stock	74	75	76	77	78	79
cod 24	1.35	1.04	1.23	1.37	1.12	1.21
cod 25-29S	.48	.55	.64	.52	.43	.54
herring 24	.39	.59	.56	.53	.47	.38
herring 25-29S	.24	.27	.27	.32	.28	.37
sprat 24	.31	.34	.49	.95	.55	.26
sprat 25-29S	.30	.30	.37	.39	.52	.32

TABLE 5. Fishing mortality coefficients for 1974-79 years used in the model.

A/

year / stock	74	75	76	77	78	79
cod 24	18	18	15	15	20	21
cod 25-29S	459	530	525	551	620	597
herring 24	147	139	130	165	235	260
herring 25-29S	1270	1280	1200	1180	1000	710
sprat 24	22	17	14	13	13	15
sprat 25-29S	916	645	520	475	300	230

B/

year / stock	74	75	76	77	78	79
cod 24 /3+/	8	8	8	6	6	10
cod 25-29S /3+/	278	374	383	361	383	420
herring 24 /2+/	120	111	100	102	164	226
herring 25-29S /3+/	720	673	663	600	557	477
sprat 24 /2+/	18	14	10	8	8	9
sprat 25-29S /2+/	667	547	330	297	233	130

TABLE 6. Mean stocks biomass estimated by the model / 10^3 tons / for 1974-79 years

a/ total stock /1+/
b/ spawning stock

parameter / stock	F variant I	F variant II	F variant III	Recruitment as 1 year old fish / 10^6 of fish/ /the same in each variant/ 80	81	82	83	84	85
cod 24	1.21	1.45	.97	38	36	28	31	33	33
cod 25-29S	.54	.65	.43	770	740	570	640	670	670
herring 24	←	.49	→	←		2100			→
herring 25-29S	←	.29	→	←		10000			→
sprat 24	←	.26	→	570	←	820			→
sprat 25-29S	←	$F_{80-82}=.32$ $F_{83-85}=.5$	→	18000	←	25000			→

TABLE 7. Fishing mortality and recruitment used in stock biomass and catch predictions for 1980-85 years /three variants of cod fishery/.

stock	variant	80	81	82	83	84	85
cod 24	I	16.4	13.9	15.1	15.3	14.5	14.6
	II	18.0	13.7	14.9	14.9	14.0	14.3
	III	14.4	13.7	15.2	15.6	14.8	14.7
cod 25-29S	I	207.0	176.0	164.2	170.3	172.7	172.7
	II	238.1	187.2	168.4	174.0	175.8	175.6
	III	172.4	159.0	154.6	161.9	165.3	165.5
herring 24	I	89.0	73.5	67.1	65.8	65.4	65.9
	II	89.3	75.2	70.6	71.1	72.2	73.4
	III	88.5	71.4	62.7	59.0	56.9	56.3
herring 25-29S	I	138.2	135.3	151.3	166.7	177.0	183.6
	II	139.0	139.4	161.4	182.8	198.4	209.1
	III	137.5	130.8	140.2	148.5	152.8	154.7
sprat 24	I	2.9	3.0	2.9	2.9	3.0	3.1
	II	2.9	3.1	3.1	3.2	3.4	3.5
	III	2.8	2.9	2.7	2.6	2.6	2.6
sprat 25-29S	I	37.5	39.3	44.4	72.5	71.0	69.9
	II	37.7	40.8	47.5	79.3	78.6	77.9
	III	37.2	37.7	41.0	65.0	62.6	61.0

TABLE 8. Catch prediction for 1980-85 years /10^3 tons/.

A/

stock \ year	variant	80	81	82	83	84	85
cod 24	I	19	18	19	19	18	19
	II	18	16	17	16	16	17
	III	20	21	22	22	22	22
cod 25-29S	I	516	478	473	477	477	487
	II	500	440	430	427	427	433
	III	533	525	530	537	543	547
herring 24	I	226	203	193	190	190	190
	II	227	210	203	203	207	210
	III	227	193	180	170	170	167
herring 25-29S	I	597	640	710	763	797	820
	II	603	660	750	823	883	920
	III	593	623	660	690	700	710
sprat 24	I	16	16	16	16	16	17
	II	16	16	17	17	18	19
	III	16	15	15	15	15	15
sprat 25-29S	I	223	240	273	280	273	273
	II	227	247	287	300	297	293
	III	220	233	257	257	250	247

B/

stock \ year	variant	80	81	82	83	84	85
cod 24	I	10	7	8	9	8	8
	II	9	5	5	6	6	6
	III	11	10	10	12	11	10
cod 25-29S	I	397	320	300	320	320	323
	II	383	287	260	270	267	270
	III	417	367	353	387	387	387
herring 24	I	193	160	150	147	147	147
	II	193	163	160	160	163	163
	III	193	150	137	127	127	123
herring 25-29S	I	353	257	267	313	347	367
	II	360	263	280	340	397	433
	III	350	250	237	263	280	290
sprat 24	I	11	12	11	11	11	12
	II	11	12	11	12	13	13
	III	11	11	10	10	10	10
sprat 25-29S	I	113	113	133	140	137	137
	II	117	123	147	160	157	153
	III	110	110	120	123	117	113

TABLE 9. Mean stock biomass predicted by the model / 10^3 tons /

A/ total stock /1+/
B/ spawning stock