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Preliminary analysis of mortality, immigration, and emigration of *Illex* populations on the Scotian Shelf

by

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INTRODUCTION

Ikeda and Sato (1976) and Hurley and Waldron (1978) have both used modifications of the cohort analysis to estimate mortality rates and initial population size for squid populations in the West Atlantic. Apart from the assumption that we are dealing with individuals from a single spawning (which seems supported, at least for 1978: the only year for which data were available to the author), the rates estimated in this way for the beginning and end of the season may include components of immigration and emigration. It is postulated that we are not dealing with a closed population, but one where the population comes onto the Shelf in spring and moves offshore in fall while the fishery is still in progress.

Analysis of Apparent Mortality Rate

Basically, three stages may be identified during the exploited phase while at least some of the Illex population is on the Shelf, or along the edge of the Shelf.

Stage I		Stage II		Stage III
Immigration of immature ♂ and ♀'s and partial availability to the gear	→	Fully recruited 'closed' population on the Shelf	→	Fully recruited but emigrating adults moving off Shelf

In terms of corresponding instantaneous rates of immigration, natural and fishing mortality and emigration, we can write for the decrease in numbers on a two weekly basis (the basic unit of time used in previous analyses); (ΔT = 2 weeks):

If Z' is the apparent mortality rate, or fitted exponential rate of decline in numbers (as evaluated, for example, by cohort analysis) on the Shelf, in theory, these rates can be decomposed as follows:

For Phase 1, $Z_1' = q_1 f_1 + M - I$ --------1

For Phase 2, $Z_2' = q_2 f_2 + M$ --------2

For Phase 3, $Z_3' = q_3 f_3 + M + \varepsilon$ --------3

Where I = immigration rate

ε = emigration rate

q_{1-3} = catchability coefficients for squid on the Shelf

f = standardized fishing effort

M = natural mortality rate

(For simplicity of treatment in what follows, it will be assumed that during Phases II and III, q is constant so that $q_1 = q_2 = q_3$ and $F = qf$.)

If the points in time separating Phases 1, 2, and 3 can be identified to within ± 2 weeks, the mortality rates given in the cohort analysis (calculated assuming a closed population with natural death rate, M) can be used to estimate I and E, if catchability coefficient and fishing effort by two weekly periods is known. This can be accomplished by subtraction of equations 2 - 1:

$I = Z_2' - Z_1' + qf_1 - qf_2$

and by subtraction of 3 - 2:

$Z_3' - Z_2' = qf_3 - qf_2 + \varepsilon$

$\varepsilon = Z_3' - Z_2' - q(f_3 - f_2)$

Recognition of Migration Phases

Three basic approaches may be of value:

1) From examination of apparent mortality rates by two-week period Thus, the rates obtained by Hurley and Waldron (1978) show low initial apparent mortality rates at the start of the fishery and high apparent rates at the end. By plotting two weekly values of F against effort units over the same period, Phase II may be identified when the plot of effort versus fishing mortality is given by a straight line.

2) Some indirect biological index (eg. sex ratio data, stages of gonad maturity) can be used to estimate a significant point at which onset of emigration begins.

3) The plot of mortality rate against time in Hurley and Mohn (1979) was used to arrive at some trial values for I and ε given the rather unrealistic assumption that the overall mortality rate obtained for Phase II ($M + F = -0.32$) applied also during Phases I and III but was modified by immigration

and emigration rates; thus:

Phase	Approximate dates	Apparent rate of decline	Assumed Z	I	ε
I	30 May, 1977	+0.98	-0.32	$\geq$ +1.30	
II	30 May to 30 Aug., 1977	-0.32	-0.32		
III	30 Aug., 1977	-0.93	-0.32		$\leq$ -0.61

Evidently, the assumed constant Z values for Phases I and III are incorrect since effort was much lower earlier and later in the season than during Phase II.

If this were true, then we can see that rates of emigration and (especially) immigration would have been significantly higher, and in any case, would be much larger than the true mortality rate. The significance of this observation will be discussed in the next section.

If corrected effort data had been available, I would have used it to arrive at a better estimate of I and ε from the above table, given that an estimate of M has been suggested (M = 0.02-0.05: Av 0.03).

Thus: Phase II: $Z' = M + q\bar{f}_2$

(numerical example: $0.32 = 0.03 + q\bar{f}_2$)

$\therefore q = 0.29/\bar{f}_2$ 1

where $\bar{f}_2$ is mean effort per two-week period in Phase II.

Phase I: $Z' = M + q\bar{f}_1 - I$

($+0.98 = 0.03 + q f_1 - I$)

$\therefore I = -0.95 + q f_1$ 2

where $\bar{f}$ is mean effort level per two-week period in Phase 1.

Phase III: $Z' = M + q\bar{f}_3 + \varepsilon$

($0.93 = 0.03 + q f_3 + \varepsilon$)

$\therefore \varepsilon = 0.90 + q f_3$ 3

RESULTS

Modelling of a Fishery With Seasonal Availability

A first attempt at modelling some of the processes involved in a three-stage fishery has been made which makes the assumptions (admittedly difficult to substantiate at this stage) that M, I, and ε are constant during each of the two-week periods they are expected to apply. A Ricker type of format was used in which all rates are assumed annual, and where the stock is divided into two components, one on, one off the Shelf, and where the outputs from each time period are fed in as inputs to the next: equations being developed for movement of animals between on- and off-Shelf areas between successive time periods (see Figure 2). Apart from Phase II (which is assumed to be a closed population), during each two-week period of Phase I, survivors moving on-Shelf during the interval are added to those already on-Shelf from the previous interval(s). During Phase III, survivors off-Shelf that arrived off-Shelf in previous interval(s) are added to those that arrived in the current interval, to contribute to the final spawning population.

Equations Used in the Model

Assuming the three phases described in the test (immigration, residence, on-Shelf, emigration), with fishing restricted to on-Shelf areas in all phases, we may consider the fate of the number of individuals (N_1) off-Shelf at the start of the immigration phase in each of a series of intervals of length ΔT (two weeks):

Phase I

The number remaining off-Shelf at the end of ΔT if natural mortality were not a factor, is given by $N' = N_1 e^{-I\Delta T}$.

a) However, the number remaining off-Shelf at the end of ΔT is determined by both immigration and natural mortality rates (both assumed constant):

$$N_2 = N_1 e^{-I\Delta T} \cdot e^{-M\Delta T}$$
$$= N\ e^{-(M+I)\Delta T}$$

b) The number of individuals that would have arrived on-Shelf by the end of ΔT if natural mortality were not a factor is given by:

$$N'' = N_1(1-e^{-I\Delta T})$$

Evidently, since ΔT is a small but finite interval, not all of those arriving on-Shelf by the end of ΔT will be available for capture on-Shelf throughout the interval, although we must assume that natural mortality occurs throughout; and without evidence to the contrary, natural mortality rate is assumed constant. As a first approximation, it is assumed that the removals due to fishing at a rate F from those individuals that arrive on-Shelf at different times during the interval, are approximately the same as the numbers that would be removed by fishing at the same rate, if all those finally arriving by the end of ΔT were available for the last half of the interval only. This assumption (which is similar to that used in Pope's cohort analysis) can best be expressed graphically (Figure 3).

If it is assumed that the fraction of the off-Shelf population that eventually survives to arrive on-Shelf by the end of ΔT is subject to natural mortality by $\Delta T/2$, then the number subject to fishing for the last half of ΔT is given by:

$$N'' = N_1(1-e^{-I\Delta T})e^{-M\Delta T/2}$$

and is then fished at rate F for a further $\Delta T/2$,

The number of survivors N_2'' is then given by:

$$N_2'' = N'' e^{-(F+M)\Delta T/2}$$

and substituting for N" and simplifying we have:

$$N_2'' = N_1(1-e^{-I\Delta T})e^{-M\Delta T/2}\ e^{-(M+F)\Delta T/2}$$
$$= N_1(1-e^{-I\Delta T})e^{-(M+F/2)}$$

To this is added the number of survivors that arrived in previous intervals, given by:

$$N_2''' = N_2'' + N_1''' \ e^{-(M+F)\Delta T}$$

where N_1'' is the total number left on-Shelf at the end of the previous interval.

The catch during ΔT of those arriving in ΔT:

This is given by $C_2 = N'' \ E[(1-e^{-(M+F)\Delta T/2})]$. Substituting for N", and simplifying:

$$C_2' = E[N_1(1-e^{-I\Delta T})e^{-M\Delta T/2}][1-e^{-(M+F)\Delta T/2}]$$

where E is the exploitation ratio, F/(F+M).

To this is added the number caught of those arriving in earlier intervals; namely:

$$C_2'' = N_1''' \ E[1-e^{-(F+M)\Delta T}]$$

Thus, $C_2 = C_2' + C_2''$ which is added to the cumulative yield (after multiplying by the age-specific weight).

Phase II

This begins when all individuals are on-Shelf (in practice, this is programmed in the HP model to begin when the number left off-Shelf is 0.01% of the initial number of recruits).

Calculations during this phase are those for a fully available stock; thus:

Number of survivors at end of ΔT: $N_2 = N_1\ e^{-(M+F)\Delta T}$

Catch during ΔT: $C_1 = N_1\ E[1-e^{-(F+M)\Delta T}]$

(The duration of this phase can either be preset, or probably more realistically, determined by the mean size attained in the population.)

Phase III

Emigration from the Shelf begins at a constant rate ε, so that:

a) The number surviving on-Shelf is:

$$N'' = N_1 e^{-(\varepsilon+M+F)\Delta T}$$

b) The number caught on-Shelf is:

$$C_2 = \frac{N_1 F}{(\varepsilon+M+F)}[1-e^{-(\varepsilon+M+F)\Delta T}]$$

c) If no natural mortality were to apply, the number moving off-Shelf would be given by:

$$N_2' = N_1(1-e^{-\varepsilon\Delta T})$$

The final number arriving off-Shelf and surviving natural mortality by end of ΔT is then:

$$N_2' = N_1(1-e^{-\varepsilon\Delta T})e^{-M\Delta T}$$

Add to this the number surviving off-Shelf from the previous intervals:

$$N_2 = N_2'' + N_2'$$

$$\text{where } N_2'' = N_1''\ e^{-M\Delta T}$$

Adding these, we get total survivors off-Shelf.

Calculations With the Squid Immigration/Emigration Model

The model can be used as a yield/recruit calculation to predict the overall yield to the fishery given input such as that in Appendix I. (This appendix also gives the HP model listing.)

An array of total catches for the model used in this way, for a combination of through-season F's, and progressive delays in onset of the fishery is given in Table 1. The delay in onset of the fishery after time zero when growth begins, and squid begin to come on-Shelf, is in effect the same as imposing a knife-edge selection curve at the mean size attained at the start of that time period. The overall yield in weight from 10^6 squid initially is shown in Table 1, scaled on the y axis for increasing F, and along the x axis for the delay from the start of immigration and growth to the onset of fishing. Numbers on- and off-Shelf, and catch in weight on-Shelf are shown in Figures 4 and 5.

The (Knife-Edge) HP Model with Lagged Onset of Fishery

The HP model with knife-edge recruitment was run for the parameters given and a delay in onset of fishing up to 12 weeks after growth begins (Figures 6 and 7) for a range of F's from 0.1 (over a 2-week time period) to 0.6. The growth curve used (from Hurley and Waldron, 1977) reaches 50 gm (approximately the mean size at which the fishery was taking squid in 1978, at the end of April), 6 weeks after the start of the simulation. The maximum yield at this lag occurs at an F = 0.3; close to the value obtained from cohort analysis in 1977. Reducing the F value at this lag to F = 0.2 will somewhat increase yield. Postponing fishing by at least a further 4 weeks is predicted to result in increases in yield. This delay may be seen as equivalent to increasing mean size at first capture to at least 106 g. Further increases with greater delays are foreseen, but an attempt to define these increments is postponed until the next section, when mesh selectivity factors are incorporated into a rather more realistic model.

Fortran Model With Partial Selection at Size

The same calculation (in Fortran IV) allows a gear selection routine (linear segmented approximation to a selection curve) to be incorporated in the model, in which the proportion retained by the gear in each biweekly period is interpolated for a given mean size, assuming all individuals passing through the gear survive (i.e. initial F is scaled for selection at size, and $F_t \leftarrow P_t F$, where P_t, the proportion retained at the mean size during interval t, is assumed to be a measure of availability at size). The results from this procedure are shown for three mesh sizes (60, 90, 100 mm) in Tables 3-8, the mesh selection parameters for which are given in Table 2, and other input variables as shown in the Appendix.

With the procedure described earlier for terminating Phases I and III, the duration of the simulation increases unduly for low values of F, thus making the results of different runs less easy to compare. The results presented in Tables 3-8 were therefore run for a fixed duration of fishing of 26 weeks from the time at which a mean size of 50 g was present in the fishery (6 to 8 weeks from the start, and roughly corresponding to the end of April, in the 1977-78 fishery). After week 32, when fishing ceased (roughly equivalent to late November when the fishery was largely over in 1977-78), the model was allowed to continue to run with F = 0, and only M operating, to determine the predicted number of survivors off-Shelf one year after the start of the simulation. The figures resulting may be then considered representative of the potential spawning stock available for the next season for each strategy, and are shown in Tables 4, 6, and 8 for 60, 90, and 100 mm mesh sizes.

From mesh selection experiments by Amaratunga et al. (1979) (and pers. comm.) the values input for mesh selection appear to show relatively little difference between 60 and 90 mm mesh so that the results are also quite similar, although with F = 0.2, and lag = 8, the yield and number of survivors are slightly greater for 90 than 60 mm. The similarity of 60 and 90 mm is contrasted with that for 100 mm, which appears much different than would be expected from geometric considerations alone. Certainly, maximum yield with 100 mm mesh occurs with higher F's and a shorter lag than at 90 mm. Further attempts to establish availability and selection with mesh size would seem warranted here before detailed conclusions from the model are pursued, although the general conclusions presented in 1) to 2) above would seem to remain valid.

Attempting to place the model roughly in a realistic time frame, it is noted that 40-60 gm was approximately the mean size in the early fishery in late April, 1978. This size occurs after week 7 in the simulation. Thus, t = 0 occurs roughly at the beginning of February as presently conceived.

<u>60 mm Mesh Size</u>

Peak yield with an 8-week lag ('77-'78 condition) occurred at F = 0.3. Yield was, however, increased progressively by a delay in the fishery of up to 10 weeks (initial mean wt. 148 g). This also doubles the number of survivors reaching the end of the year. Reduction in F necessitated a smaller delay for the same effect, and vice versa (Figure 8).

<u>90 mm Mesh Size</u>

With the selection parameters given, 90 mm is closely similar to 60 mm in effect, except that the optimum yield at a given lag occurs at slightly higher F's.

100 mm Mesh Size

Included mostly for reference, peak yield at this mesh size occurs at the highest F levels considered (F = 0.6) and the benefits of delaying the fishery are reduced, presumably because availability is postponed until later in the fishery anyway, at this higher mesh size.

DISCUSSION

Some Points of Relevance to Management of Squid Stocks

Two key observations can be made as a result of the foregoing that may be relevant to management of this fishery.

1) In terms of ensuring a "safe" level of population for an annual species to reproduce the stock in the following year, the key control point seems to be to ensure that an adequate number of animals (N) survive until the time at which emigration begins. After that point in time, the proportion of N available to the fishery will not exceed $F/(F+M+\varepsilon)$. (For values postulated earlier, this means that the proportion caught subsequent to Phase III beginning will not much exceed 30%.) The actual proportion surviving to spawn is, of course, unknown since the time between the end of the fishing period and onset of spawning is unknown at present. However, the proportion surviving to the end of the fishery will probably not exceed $\varepsilon/(F+M+\varepsilon)$ (or for the same parameter values above, roughly 60%). In the simulation, the number of survivors of fishing are reduced further by natural mortality, to give the number still alive at the end of one year, as the best measure of spawning potential.

2) The question of what is the best method of ensuring adequate survival may be rephrased in terms of the strategy that results in a given number surviving to onset of Phase III. Postponing onset of the fishery or controlling fishing intensity seem the two obvious options, and these two measures have roughly equivalent effects (i.e. for a low F, the fishery need not be postponed as long).

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TABLE 1. Cumulative weight of the catch with the HP "knife-edge" simulation. (X- Axis is F, Y- Axis is the onset of the fishery, progressively delayed by up to 12 weeks from the start of growth. The second column refers to the weight of the squid at the start of the fishery.)

Delay (weeks)	Weight (kgs)	0.1	0.2	0.3	0.4	0.5	0.6	F
0	0.002	[51482.29]	50050.89	41508.90	33815.29	28028.65	23798.67	
2	0.009	53288.92	[53495.71]	45700.76	38255.64	32509.76	28244.93	
4	0.023	56314.11	[61345.50]	55693.39	49178.00	43785.96	39624.04	
6	0.041	59863.71	[69820.50]	67139.98	62168.48	57555.20	53789.68	
8	0.062	62378.11	77274.65	[77971.48]	74960.34	71452.26	68327.86	
10	0.084	63502.53	82925.48	[87134.08]	86350.83	84193.17	81894.80	
12	0.106	63092.94	86358.94	94023.96	[95639.75]	95030.52	93721.99	

KEY: Bracketed values are eumetric yields for each delay period:
Underlined values are maximum yields at each F level.
Dashed line is first estimate of onset of fishery in 1977-78.
Values in box are tentative estimates of 1977-78 position.

TABLE 2. Mean weight of squid at 5 percentile points (kg) for each of 3 mesh sizes. (Data from Amaratunga, pers. comm.)

% Retention	Mesh size (mm)		
	60	90	100
0	0.019	0.019	0.081
25	0.031	0.030	0.116
50	0.047	0.054	0.148
75	0.081	0.098	0.199
100	0.137	0.160	0.445

TABLE 3. Number surviving off-Shelf at the end of the squid population simulation with a mesh size of 60 mm.*

Delay (weeks)	Weight (kgs)	F						
		0.0	0.1	0.2	0.3	0.4	0.5	0.6
0	0.002	352923.9	143139.4	58898.8	24537.8	10330.7	4388.2	1878.0
2	0.009	352923.9	143139.4	58898.8	24537.8	10330.7	4388.2	1878.0
4	0.023	352923.9	143139.4	58898.8	24537.8	10330.7	4388.2	1878.0
6	0.041	352923.9	143141.7	58900.7	24538.9	10331.4	4388.5	1878.2
8	0.062	352923.9	146729.9	61889.4	26429.3	11405.4	4965.7	2178.2
10	0.084	352923.9	154263.6	68406.6	30711.4	13933.1	6377.2	2940.7
12	0.106	352923.9	166289.8	79488.1	38468.0	18812.3	9281.5	4613.4
14	0.128	352923.9	179352.5	92466.6	48264.1	25457.0	13546.5	7262.3
16	0.148	352923.9	193536.6	107670.4	60644.0	34516.7	19820.0	11465.9
18	0.167	352923.9	213912.6	131535.4	81885.3	51513.3	32694.1	20904.7
20	0.184	352923.9	236433.4	160690.0	110567.0	76879.3	53930.0	38113.8
22	0.199	352923.9	261325.7	196306.7	149294.9	114736.7	88960.2	69489.1
24	0.213	352923.9	288838.6	239817.8	201587.9	171235.9	146744.1	126693.8
26	0.225	352923.9	219247.9	292972.7	272197.0	255556.4	242061.6	230990.1
28	0.235	352923.9	335842.1	322084.1	310924.6	301807.6	294305.3	288087.9

(*For key to table, please see Table 1.)

TABLE 4. Yield per recruit with a mesh size of 60 mm.*

Delay (weeks)	Weight (kgs)	F 0.0	0.1	0.2	0.3	0.4	0.5	0.6
0	0.002	0.0	60650.1	78172.2	[80689.9]	78373.1	74839.6	71312.7
2	0.009	0.0	60650.1	78172.2	[80689.9]	78373.1	74839.6	71312.7
4	0.023	0.0	60650.1	78172.2	[80689.9]	78373.1	74839.6	71312.7
6	0.041	0.0	60650.7	78174.0	[80692.7]	78376.7	74843.9	71317.4
8	0.062	0.0	61278.0	80333.1	[84164.7]	82821.9	80003.7	77021.7
10	0.084	0.0	61772.3	83352.9	89430.7	[89725.8]	88055.4	85891.5
12	0.106	0.0	61334.3	85936.0	94988.8	[97529.8]	97436.2	96367.8
14	0.128	0.0	59718.0	86589.9	98309.0	103025.2	104532.9	[104610.1]
16	0.148	0.0	56954.2	85258.2	99231.1	105974.6	109058.0	[110296.7]
18	0.167	0.0	51851.8	80782.0	97039.6	106196.7	111331.4	[114168.9]
20	0.184	0.0	45297.5	73387.3	91035.1	102245.7	109430.6	[114064.9]
22	0.199	0.0	37345.8	62864.0	80572.4	93037.4	101925.0	[108334.8]
24	0.213	0.0	28039.7	48918.7	64723.0	76872.7	86348.4	[93836.1]
26	0.225	0.0	17405.3	31148.7	42162.0	51117.0	58501.4	[64672.7]
28	0.235	0.0	8852.3	16070.5	22005.8	26928.5	31047.2	[34523.5]

*(For key to table, see Table 1.)

TABLE 5. Number surviving off-Shelf at the end of the squid population simulation with a mesh size of 90 mm*

Delay (weeks)	Weight (kgs)	F 0.0	0.1	0.2	0.3	04	05	06
0	0.002	352923.9	150321.2	64957.0	28419.0	12564.7	5604.7	2518.9
2	0.009	352923.9	150321.2	64957.0	28419.0	12564.7	5604.7	2518.9
4	0.023	352923.9	150321.2	64957.0	28419.0	12564.7	5604.7	2518.9
6	0.041	352923.9	150323.2	64958.6	28420.1	12565.4	5605.1	2519.1
8	0.062	352923.9	154098.9	68261.4	30614.1	13874.5	6344.0	2922.4
10	0.084	352923.9	162001.1	75440.9	35567.9	16945.6	8145.0	3944.2
12	0.106	352923.9	170396.4	83462.5	41389.0	20740.6	10485.6	5340.7
14	0.128	352923.9	183718.7	97023.6	51875.3	28027.9	15277.6	8389.7
16	0.148	352923.9	198191.4	112912.0	65125.6	37959.1	22320.9	13223.2
18	0.167	352923.9	213912.6	131535.4	81885.3	51513.3	32694.1	20904.7
20	0.184	352923.9	236433.4	160690.0	110567.0	76879.3	53930.0	38113.8
22	0.199	352923.9	261325.7	196306.7	149294.9	114736.7	88960.2	69489.1
24	0.213	352923.9	288838.6	239817.8	201587.9	171235.9	146744.1	126693.8
26	0.225	352923.9	319247.9	292972.7	272197.0	255556.4	242061.6	230990.1
28	0.235	352923.9	335842.1	322084.1	310924.6	301807.6	294305.3	288087.9

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TABLE 6. Cumulative weight of the catch at the end of the squid population simulation with a mesh size of 90 mm.*

Delay (weeks)	Weight (kgs)	F 0.0	0.1	0.2	0.3	0.4	0.5	0.6
0	0.002	0.0	59620.8	78293.7	[81837.6]	80102.3	76810.6	73322.9
2	0.009	0.0	59620.8	78293.7	[81837.6]	80102.3	76810.6	73322.9
4	0.023	0.0	59620.8	78293.7	[81837.6]	80102.3	76810.6	73322.9
6	0.041	0.0	59621.4	78295.2	[81840.1]	80105.5	76814.4	73327.2
8	0.062	0.0	60223.9	80464.6	[85407.6]	84740.0	82244.7	79365.5
10	0.084	0.0	60663.6	83494.5	90867.9	[92059.5]	90922.4	89043.2
12	0.106	0.0	60315.3	85206.2	94707.6	97577.9	[97673.4]	96691.7
14	0.128	0.0	58626.9	85738.4	97939.6	103061.2	104840.0	[105072.6]
16	0.148	0.0	55787.9	84272.7	98763.7	106010.7	109486.5	[110999.5]
18	0.167	0.0	51851.8	80782.0	97039.6	106196.7	111331.4	[114168.9]
20	0.184	0.0	45297.5	73387.3	91035.1	102245.7	109430.6	[114064.9]
22	0.199	0.0	37345.8	62864.0	80572.4	93037.4	101925.0	[108334.8]
24	0.213	0.0	28039.7	48918.7	64723.0	76872.7	86348.4	[93836.1]
26	0.225	0.0	17405.3	31148.7	42162.0	51117.0	58501.4	[64672.7]
28	0.235	0.0	8852.3	16070.5	22005.8	26928.5	31047.2	[34523.5]

*(For key to table, see Table 1.)

TABLE 7. Number surviving off-Shelf at the end of the squid population simulation with a mesh size of 100 mm.*

Delay (weeks)	Weight (kgs)	F 0.0	0.1	0.2	0.3	0.4	0.5	0.6
0	0.002	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
2	0.009	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
4	0.023	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
6	0.041	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
8	0.062	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
10	0.084	352923.9	246360.9	173559.2	123270.0	88181.6	63478.2	45946.8
12	0.106	352923.9	246370.3	173572.5	123284.2	88194.9	63490.3	45957.3
14	0.128	352923.9	246456.4	173693.8	123413.5	88318.5	63601.3	46053.8
16	0.148	352923.9	252739.4	182662.7	133094.7	97674.9	72132.4	53562.4
18	0.167	352923.9	259249.9	192194.6	143647.6	108134.9	81914.1	62392.6
20	0.184	352923.9	272659.9	212592.0	167111.6	132305.2	105407.8	84440.3
22	0.199	352923.9	286863.7	235318.4	194612.1	162104.4	135876.8	114518.8
24	0.213	352923.9	301902.1	260637.4	226851.4	198864.5	175427.7	155603.9
26	0.225	352923.9	325870.9	303665.7	285285.4	269944.6	257037.0	246091.8
28	0.235	352923.9	339119.4	327504.4	317688.0	309354.0	302245.8	296155.7

*(For key to table, see Table 1.)

TABLE 8. Cumulative weight of the catch at the end of the squid population simulation with a mesh size of 100 mm.*

Delay (weeks)	Weight (kgs)	F 0.0	0.1	0.2	0.3	0.4	0.5	0.6
0	0.002	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
2	0.009	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
4	0.023	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
6	0.041	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
8	0.062	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
10	0.084	0.0	39381.8	64868.4	81394.0	92091.6	98970.3	[103331.0]
12	0.106	0.0	39380.7	64868.2	81395.6	92095.4	98976.2	[103339.2]
14	0.128	0.0	39365.9	64856.3	81395.0	92109.7	99006.2	[103384.3]
16	0.148	0.0	37956.5	63317.4	80354.1	91838.1	99586.2	[104801.9]
18	0.167	0.0	36219.4	61121.4	78367.5	90383.7	98794.2	[104697.2]
20	0.184	0.0	32191.6	55498.1	72526.6	85072.7	94385.9	[101345.4]
22	0.199	0.0	27575.3	48514.5	64575.0	77010.7	86725.6	[94377.1]
24	0.213	0.0	22430.4	40205.5	54439.0	65951.1	75350.9	[83094.9]
26	0.225	0.0	13966.5	25534.8	35206.2	43366.6	50314.6	[56282.6]
28	0.235	0.0	7145.5	13215.3	18398.3	22848.1	26689.4	[30023.9]

*(For key to table, see Table 1.)

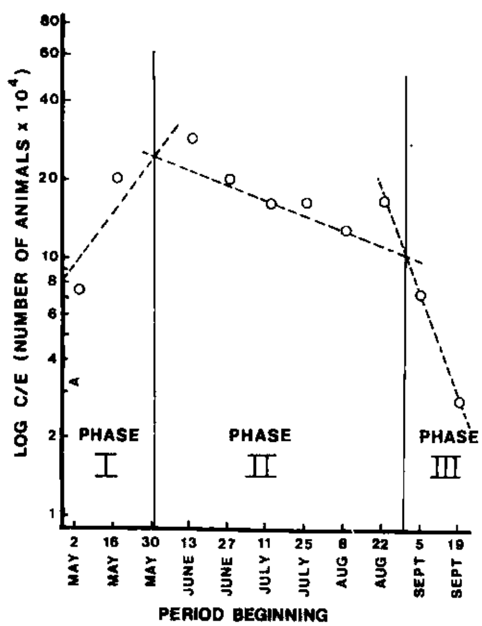


Fig. 1. Graph of log (C/E) versus time during the 1977 fishing season. Dashed lines fitted by eye represent hypothesized stages in migration cycle. (C = catch in numbers, and E = effective squid effort from Hurly and Mohn, 1978.)

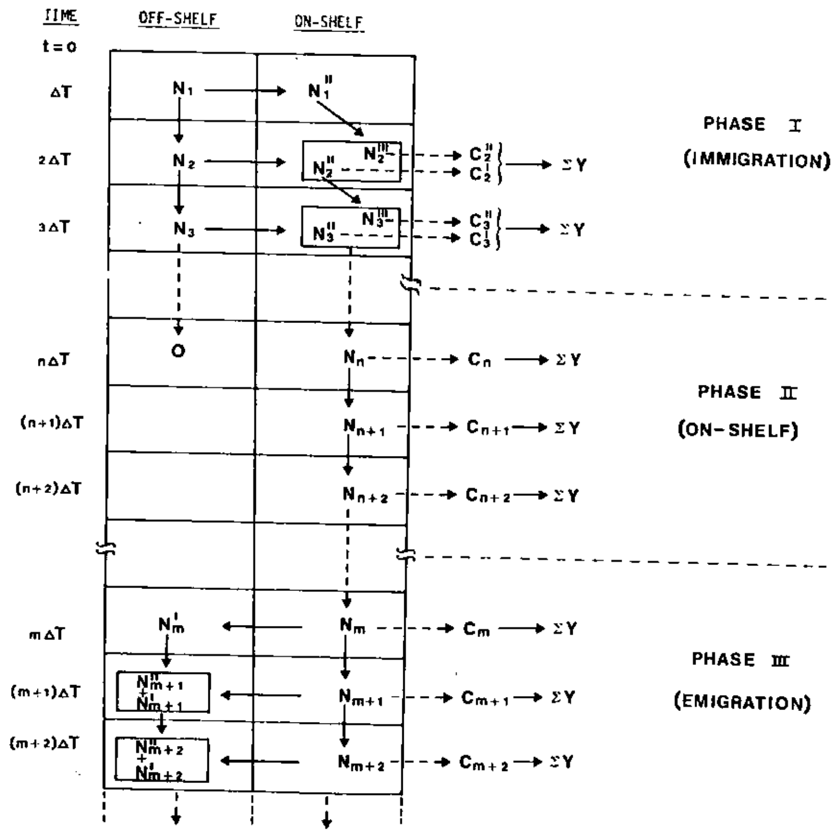


Figure 2. Diagrammatic structure of the migration model.

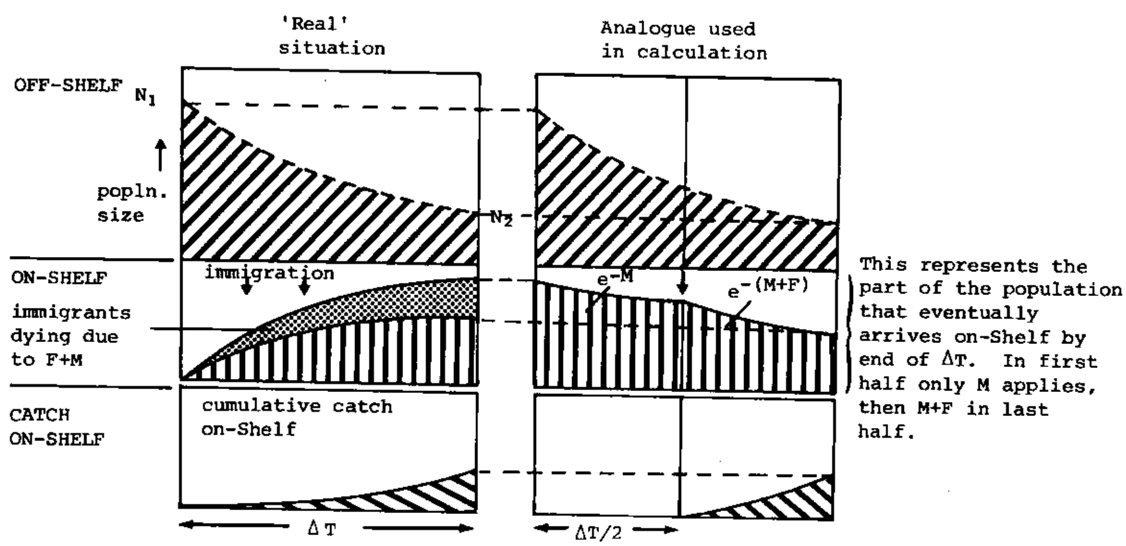


Figure 3. Demonstration of method of approximation of immigration phase.

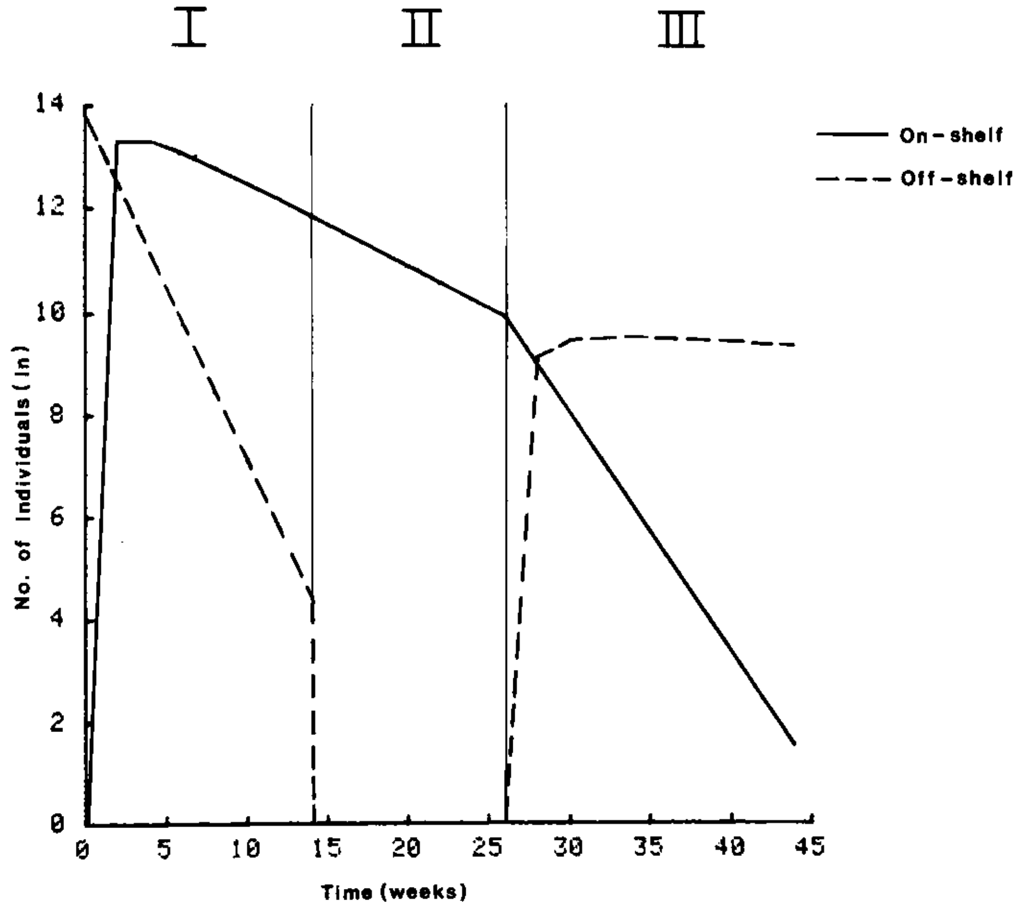
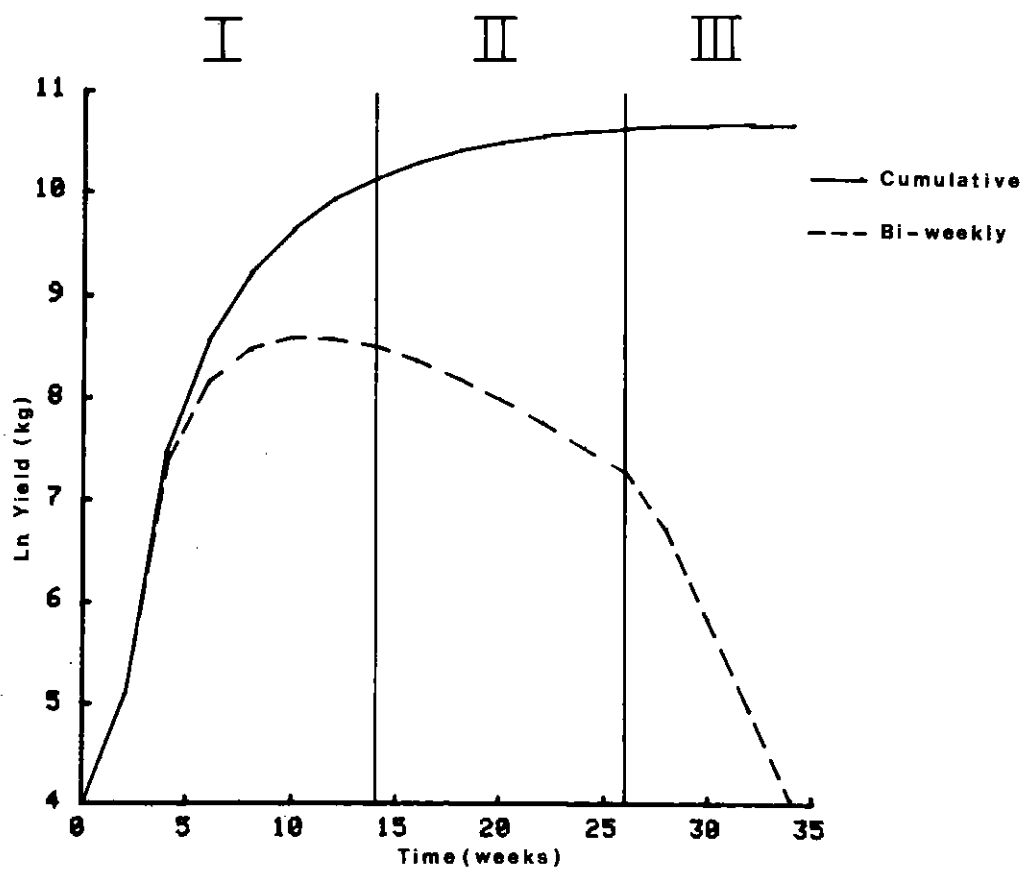


Figure 4. Log no. of individuals off (dashed line) and on (solid line) the Shelf during the course of a simulation with zero lag (knife-edge recruitment). Roman numerals indicate phase no.



C 3

Figure 5. Log of cumulative and bi-weekly catch in weight with delay in the onset of fishing for the simulation shown

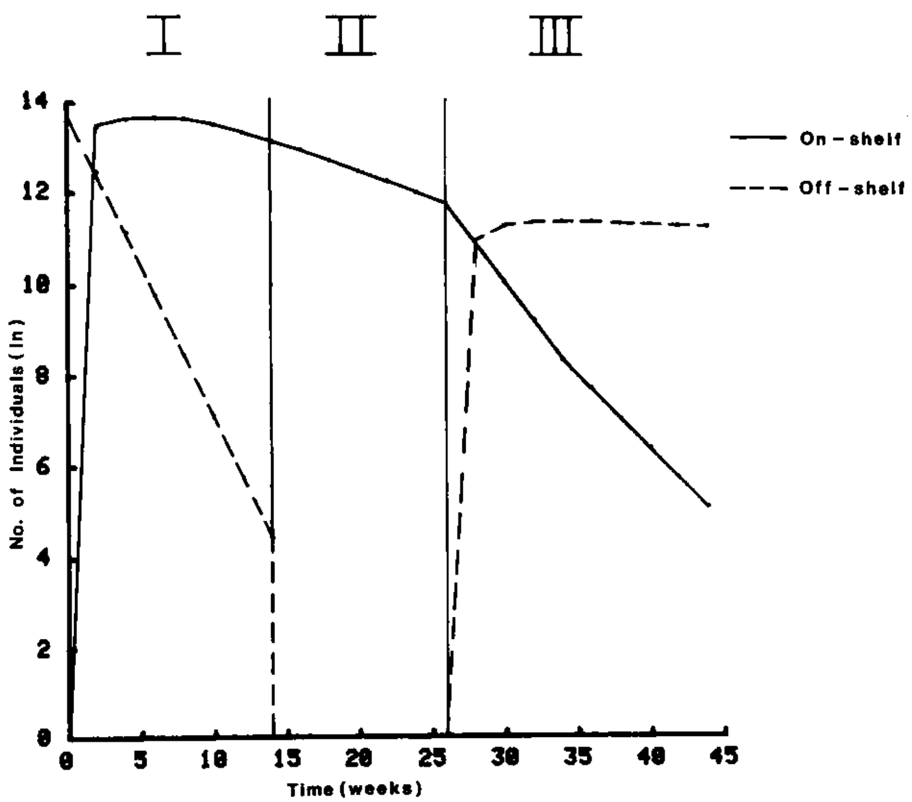


Figure 6. Log no. of individuals off (dashed line) and on (solid line) the Shelf during the course of a simulation with a delay in onset of fishing until the 8th week (partial recruitment version). Roman numerals indicate phase no.

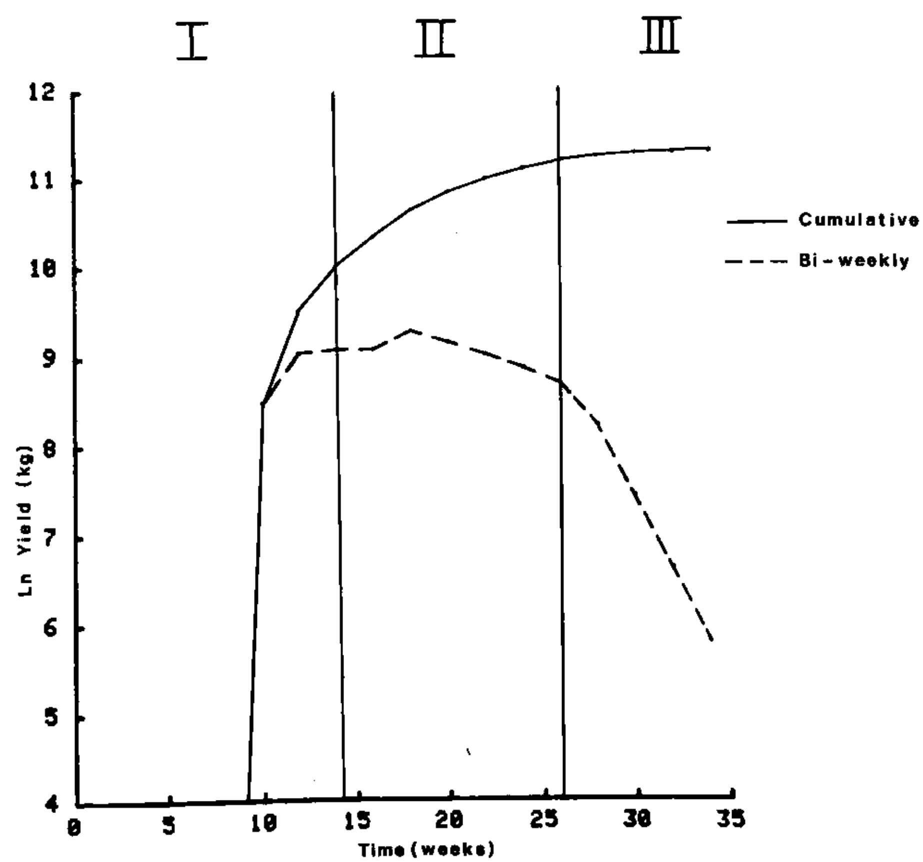


Figure 7. Log of cumulative and by-weekly catch in weight with an 8-week delay in the onset of fishing for the simulation shown in Figure 5.

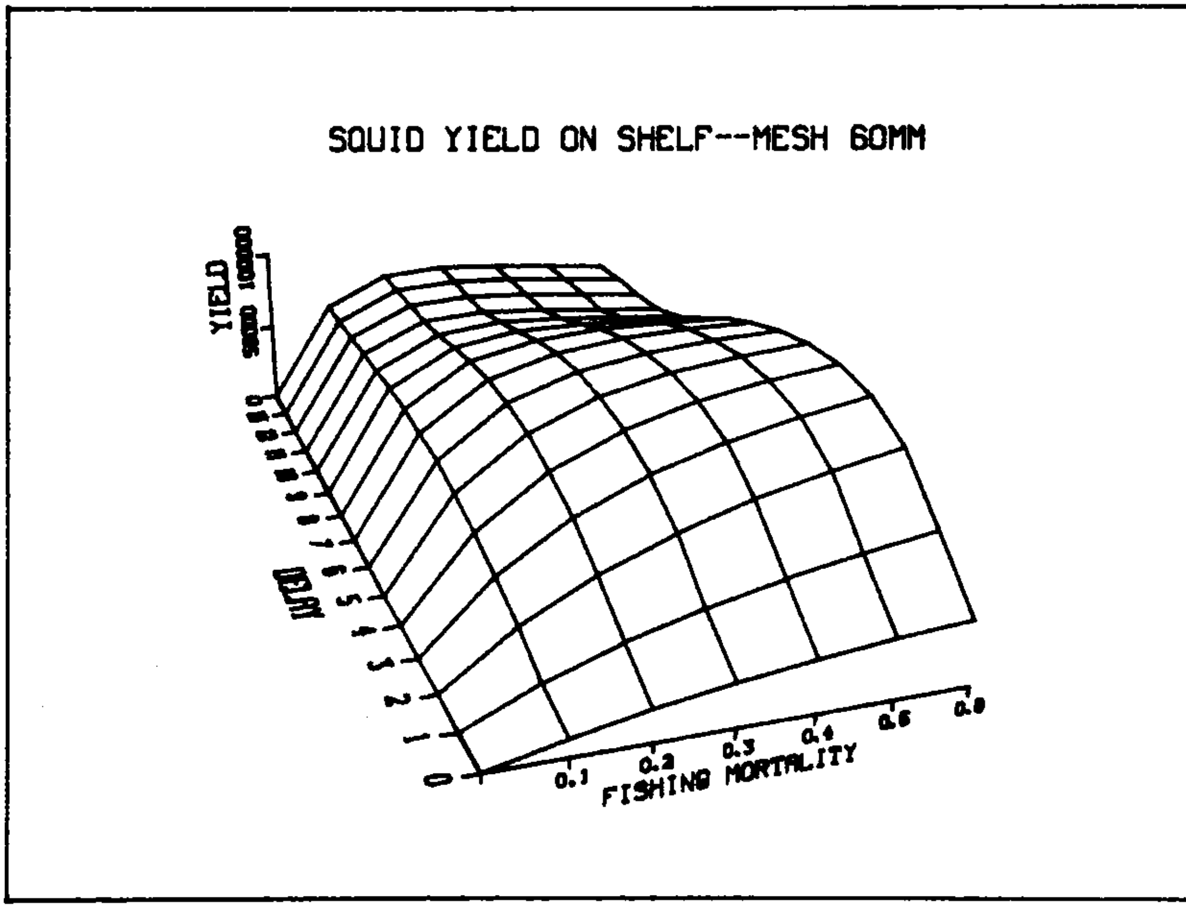
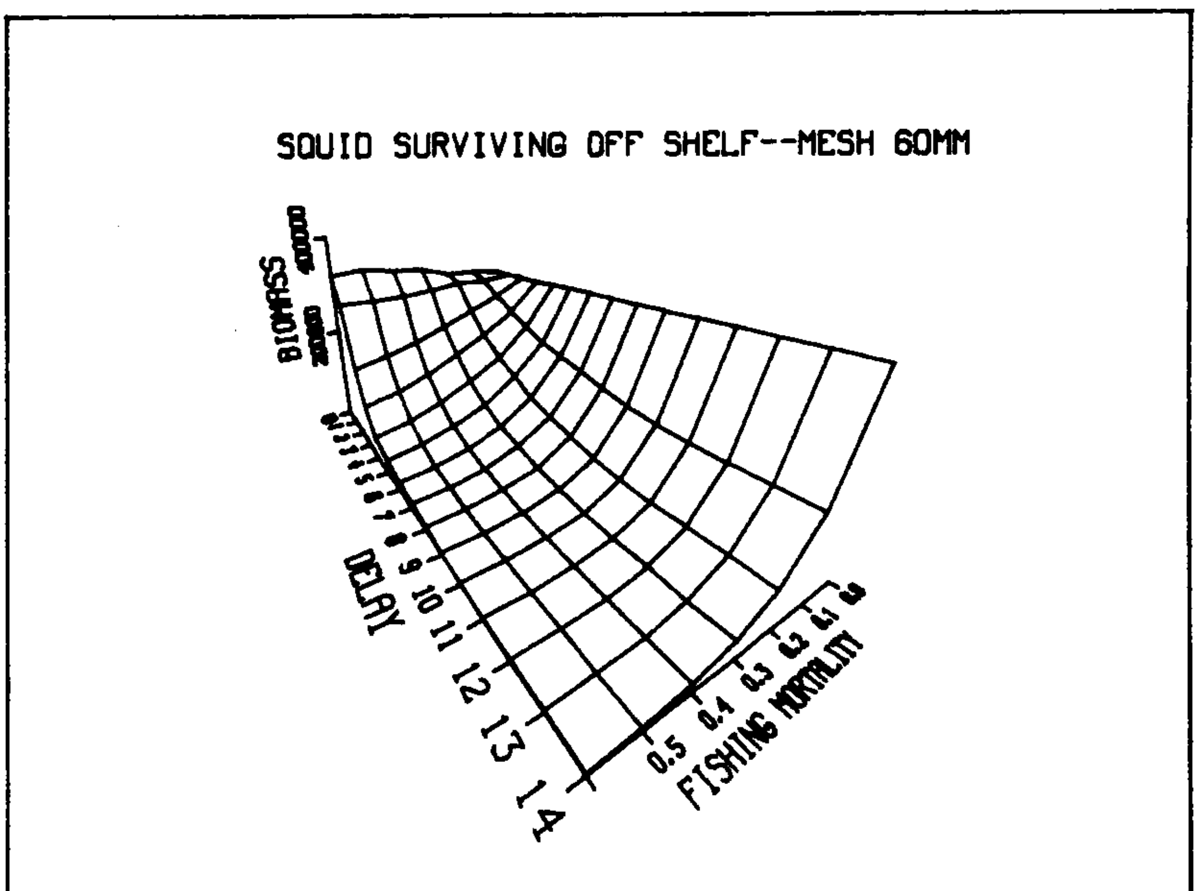


Figure 8a. Yield surface for a combination of F's and delays at onset of fishing using 60 mm mesh. (Delays are in 2-week intervals.)



C 5

Figure 8b. Number of individuals surviving at the end of one year with a combination of F's

Appendix I. User instructions, input values used, and HP programme listing.

1 SQUID SIMULATION WITH ONSET OF FISHING DELAY - PHASE I CARD 1 2

INPUT OUTPUT

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Read in both sides of Card 1				
2	Enter input parameters			A	
3	Natural mortality (annual)		1.04	R/S	
4	Fishing mortality (annual) if fishing starts at the onset of growth. If a delay is desired, enter Ø.		7.28	R/S	
5	Immigration rate (annual)		33.8	R/S	
6	Duration of ΔT		.0385	R/S	
7	Emigration rate (annual)		15.9	R/S	
8	Initial population size off-Shelf (N_0)		10^6	R/S	
9	Von Bertalanffy parameter (K)		.164	R/S	
10	Von Bertalanffy assymptotic wt. parameter (W_∞)	kg.	.300	R/S	
11	Length-weight parameter (b)		2.72	R/S	
12	No. of period in which fishing commences. If fishing starts from the beginning, enter Ø.		0	R/S	
13	No. of periods in Phase II		6	R/S	
14	Calculation of output of Phase I			B	
15	Enter fishing mortality when prompted by period number if delay has been selected.		7.28	R/S	
16	Read in both sides of card 2				
17	Calculations of output for Phases II and III			C	

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	GSBA	27 11	
	*LBLA	21 11	Input parameters +
	CLRG	16-53	initial values for
	P≠S	16-51	variables
	CLRG	16-53	
	R/S	51	
	STOA	35 11	M
	R/S	51	
	STOB	35 12	F
010	R/S	51	
	STOC	35 13	I
	R/S	51	
	STOD	35 14	ΔT
	R/S	51	
	STOE	35 15	ε
	R/S	51	
	STO0	35 00	No. off-Shelf
	P≠S	16-51	
	R/S	51	
020	STO1	35 01	K
	R/S	51	
	STO2	35 02	W_∞
	R/S	51	
	STO6	35 06	b
	R/S	51	
	STO8	35 08	Delay
	R/S	51	
	STOI	35 46	# periods in PhaseII
	ISZI	16 26 46	
030	P≠S	16-51	
	R/S	51	
	*LBLB	21 12	Phase I: Immigration
	1	01	
	0	00	
	0	00	
	RCL0	36 00	
	X≤Y?	16-35	Test to see if # off-
	GTOC	22 13	shelf is ≤.01% of
	P≠S	16-51	initial. If so, go
040	1	01	to Phase II.
	ST+7	35-55 07	
	P≠S	16-51	
	SPC	16-11	
	RCLA	36 11	
	RCLC	36 13	
	+	-55	
	RCLD	36 14	
	x	-35	
	CHS	-22	
050	e^x	33	
	STO4	35 04	$e^{-(M+I)\Delta T}$
	RCLC	36 13	
	RCLD	36 14	
		-35	
	CHS	-22	
	e^x	33	
	CHS	-22	
	STO3	35 03	$-e^{-I\Delta T}$
	GTO4	22 04	
060	*LBL5	21 05	Subroutine for cal-
	P≠S	16 51	culating time-
	RCL7	36 07	specific lengths
	RCL1	36 01	
	x	-35	
	CHS	-22	
	e^x	33	
	CHS	-22	
	1	01	
	+	-55	
070	RCL6	36 06	
	y^x	31	
	RCL2	36 02	
	x	-35	
	P≠S	16-51	
	PRTX	-14	$W_t=W_\infty(1-e^{-K(t-t_0)b})$
	RTN	24	
	*LBL4	21 04	
	RCLA	36 11	
	RCLD	36 14	
080	x	-35	
	CHS	-22	
	e^x	33	
	STO2	35 02	$e^{-M\Delta T}$
	LN	32	
	2	02	
	÷	-24	
	e^x	33	
	P≠S	16-51	
	STO4	35 04	$e^{-M\Delta T/2}$
090	RCL7	36 07	
	RCL8	36 08	
	X≠Y?	16-32	
	GTO6	22 06	
	R/S	51	
	STOB	35 12	
	*LBL6	21 06	
	P≠S	16-51	
	RCLB	36 12	
	RCLA	36 11	
100	+	-55	
	RCLD	36 14	
	x	-35	
	2	02	
	÷	-24	
	CHS	-22	
	e^x	33	
	CHS	-22	
	1	01	
	+	-55	
110	RCL3	36 03	
	1	01	
	+	-55	
	x	-35	
	RCL0	36 00	
	x	-35	
	P≠S	16-51	
	RCL4	36 04	
	P≠S	16-51	
	x	-35	
120	RCLA	36 11	
	RCLB	36 12	
	+	-55	
	LSTX	16-63	
	X≷Y	-41	
	÷	-24	
	STO5	35 05	E = (F/F+M)
	x	-35	
	STO7	35 07	C_1 = Catch of squid
	SPC	16-11	coming on-Shelf in
130	RCL9	36 09	ΔT (nos.)
	RCL5	36 05	
	x	-35	N_1E
	RCLA	36 11	
	RCLB	36 12	
	+	-55	
	RCLD	36 14	
	x	-35	
	CHS	-22	
	e^x	33	$e^{-(F+M)\Delta T}$
140	STO6	35 06	
	CHS	-22	
	1	01	
	+	-55	
	x	-35	C_2 = Catch of squid
	RCL7	36 07	on-Shelf before ΔT
	+	-55	(nos.)
	PRTX	-14	C_t = Total catch
	GSB5	23 05	during ΔT (nos.)
	x	-35	
150	PRTX	-14	C_t = Total catch
	P≠S	16-51	during ΔT (kg.)
	ST+0	35-55 00	
	RCL0	36 00	
	PRTX	-14	$Y = \overline{W}\ (C_1 + C_2)$ cumu-
	P≠S	16-51	lative catch (kg.)
	RCL0	36 00	
	RCLA	36 11	
	RCLD	36 14	
	x	-35	
160	CHS	-22	
	2	02	
	÷	-24	
	e^x	33	
	x	-35	$N_1e^{-M\Delta T/2}$
	RCL6	36 06	
	LN	32	$-(F+M)\Delta T$
	.	-62	
	5	05	
	x	-35	
170	e^x	33	
	x	-35	$N_1e^{-(F+M)\Delta T/2}$
	RCL3	36 03	$\times\ e^{-M\Delta T/2}$
	1	01	
	+	-55	
	x	-35	
	STO8	35 08	N_2'=survivors of
	RCL9	36 09	those arriving on-
	RCL6	36 06	Shelf in ΔT.
	x	-35	$N_2''=N_1e^{-(F+M)\Delta T}$
180	RCL8	36 08	
	+	-55	
	PRTX	-14	$N_2'+N_2''$ = survivors
	STO9	35 09	on-Shelf
	RCL4	36 04	
	RCL0	36 00	
	x	-35	
	STO0	35 00	$N_2=N(1-e^{-(M+I)\Delta T})$
	PRTX	-14	survivors off-Shelf
	GTOB	22 12	
190	*LBLC	21 13	
	RTN	24	
	R/S	51	
200			
210			
220			

REGISTERS

0 N_0	1 Pop.-off	2 $e^{-M\Delta T}$	3 $-e^{-I\Delta T}$	4 $e^{-(M+I)\Delta T}$	5 E	6 $e^{-(F+M)\Delta T}$	7 C_1	8 Temporary Pop.-on	9 Pop.-on
S0 ΣY	S1 K	S2 W_∞	S3	S4	S5	S6 b	S7 t	S8 Lag	S9
A M	B F	C I	D ΔT	E ε	I Length of Phase II				

LABELS

A Input	B Output	C	D	E
a	b	c	d	e
0	1	2	3	4
5	6	7	8	9

FLAGS

0
1
2
3

SET STATUS

FLAGS	TRIG	DISP
ON OFF		
0 ☐ ☐	DEG ☐	FIX ☒
1 ☐ ☐	GRAD ☐	SCI ☐
2 ☐ ☐	RAD ☐	ENG ☐
3 ☐ ☐		n 2

User Instructions

SQUID SIMULATION WITH ONSET OF FISHING DELAY - PHASE II AND III CARD 2

OUTPUT

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL0	21 13	Phase II: on-Shelf
	*LBL9	21 09	
	SPC	16-11	
	SPC	16-11	
	DSZI	16 25 46	
	GTOE	22 15	
	GTOD	22 14	
	*LBLE	21 15	
	P⇄S	16-51	
010	1	01	
	ST+7	35-55 07	
	RCL7	36 07	
	RCL8	36 08	
	X≠Y?	16-32	
	GTO6	22 06	
	R/S	51	
	STOB	35 12	
	*LBL6	21 06	
	P⇄S	16-51	
020	RCLA	36 11	
	RCLB	36 12	
	+	-55	
	LSTX	16-63	
	X⇄Y	-41	
	÷	-24	
	STO5	35 05	
	RCL9	36 09	
	x	-35	
	RCLA	36 11	
030	RCLB	36 12	
	+	-55	
	RCLD	36 14	
	x	-35	
	CHS	-22	
	e^x	33	
	STO6	35 06	
	CHS	-22	
	1	01	
	+	-55	
040	x	-35	EN = Catch on-Shelf (nos.)
	PRTX	-14	
	GSB5	23 05	
	x	-35	
	PRTX	-14	EN(1-$e^{(-F+M)\Delta T}$) = catch on-Shelf (kg.)
	P⇄S	16 51	
	ST+0	35-55 00	
	RCL0	36 00	
	PRTX	-14	Y = Cumulative yield
	P⇄S	16-51	
050	RCL9	36 09	
	RCL6	36 06	
	x	-35	
	STO9	35 09	
	PRTX	-14	Survivors on-Shelf
	GTOC	22 13	
	*LBLD	21 14	Phase II: Emigration
	SPC	16-11	
	SPC	16-11	
	P⇄S	16-51	
060	1	01	
	ST+7	35-55 07	
	P⇄S	16-51	
	RCL9	36 09	
	1	01	
	0	00	
	X>Y?	16-34	If <10 squid left on-Shelf, terminate program.
	GTOE	22 15	
	RCLE	36 15	
	RCLA	36 11	
070	+	-55	
	RCLB	36 12	
	+	-55	
	STO3	35 03	F+M+ε
	RCLD	36 14	
	x	-35	
	CHS	-22	
	e^x	33	
	STO6	35 06	$e^{-(F+M+\varepsilon)\Delta T}$
	CHS	-22	
080	1	01	
	+	-55	
	RCLB	36 12	
	x	-35	
	RCL3	36 03	
	÷	-24	
	RCL9	36 09	
	x	-35	
	PRTX	-14	Catch on-Shelf (nos)
	GSB5	23 05	
090	x	-35	
	PRTX	-14	Catch on-Shelf (kg.)
	P⇄S	16-15	
	ST+0	35-55 00	
	RCL0	36 00	
	PRTX	-14	Y = Cumulative yield
	P⇄S	16-51	
	RCLE	36 15	
	RCLD	36 14	
	x	-35	
100	CHS	-22	
	e^x	33	
	CHS	-22	
	1	01	
	+	-55	$1-e^{-\varepsilon\Delta T}$
	RCL2	36 02	
	x	-35	
	RCL9	36 09	
	x	-35	
	STO1	35 01	Survivors arriving off-Shelf
110	RCL2	36 02	
	RCL0	36 00	Survivors already off-Shelf
	x	-35	
	RCL1	36 01	
	+	-55	
	STO0	35 00	
	PRTX	-14	Total survivors off-Shelf
	RCL6	36 06	
	RCL9	36 09	
	x	-35	
120	STO9	35 09	
	PRTX	-14	Survivors on-Shelf
	GTOD	22 14	
	*LBL5	21 05	
	P⇄S	16-51	
	RCL7	36 07	
	RCL1	36 01	
	x	-35	
	CHS	-22	
	e^x	33	
130	CHS	-22	
	1	01	
	+	-55	
	RCL6	36 06	
	y^x	31	
	RCL2	36 02	
	x	-35	
	P⇄S	16 51	
	PRTX	-14	Meat weight during ΔT
	RTN	24	
140	*LBLE	21 15	
	SPC	16-11	
	P⇄S	16-51	
	RCL0	36 00	
	PRTX	-14	Cumulative yield in Phases I, II, & III
	+	-55	
	RTN	24	

REGISTERS

0	1	2	3	4	5	6	7	8	9
N_0	Pop.-off	$e^{-M\Delta T}$	ε+M+F	$e^{-(M+I)\Delta T}$	E	$e^{-(\varepsilon+M+F)}$	C_1	Temporary Pop.-on	Pop.-on
S0 ΣY	S1 K	S2 W_∞	S3	S4	S5	S6 b	S7 t	S8 Lag	S9

A	B	C	D	E	I
M	F	I	ΔT	ε	Length of Phase II

LABELS

A	B	C	D	E
		OUTPUT		
a	b	c	d	e
0	1	2	3	4
5	6	7	8	9

FLAGS: 0, 1, 2, 3

SET STATUS

FLAGS (ON OFF)	TRIG	DISP
0 ☐ ☐	DEG ☐	FIX ☒
1 ☐ ☐	GRAD ☐	SCI ☐
2 ☐ ☐	RAD ☐	ENG ☐
3 ☐ ☐		n 2