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SOME APPROACHES TO ELUCIDATION OF THE DYNAMICS OF SWORDFISH (*Xiphias gladius*) POPULATIONS

by

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ABSTRACT

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In the absence of good estimates of growth and mortality for Atlantic swordfish stocks, preliminary assessment must be based on a range of parameter values obtained for other stocks, and by comparison with estimates from other large pelagic fish populations occupying a similar niche in the ecosystem. The relative merits of alternative approaches to swordfish stock assessment are compared and a preliminary yield-per-recruit analysis used to illustrate the consequences of a broad range of parameter inputs for management of longline and harpoon fisheries.

Key words: Swordfish, population dynamics, stock assessment

RÉSUMÉ

Caddy, J. F. 1977. Some approaches to elucidation of the dynamics of swordfish (*Xiphias gladius*) populations. Fish. Mar. Serv. MS Rep. 1439, 10 p.

En l'absence de valides calculs de croissance et mortalité pour les stocks d'espadon de l'Atlantique, une évaluation préliminaire doit être basée sur une rangée de valeurs paramètres obtenues pour d'autres stocks, et par comparaison avec des calculs de populations de gros poissons pélagiques habitant une niche semblable dans l'écosystème. Les mérites relatifs d'approches alternatives à l'évaluation du stock d'espadon sont comparés et une analyse préliminaire de rendement par recrue est employée pour illustrer les conséquences d'une vaste rangée de valeurs paramètres pour la gestion de la pêche à longue ligne et au harpon.

INTRODUCTION

Most of the standard techniques of stock assessment require at least preliminary estimates of the growth and mortality parameters of the population, and some idea of stock identities. For the most part these estimates are lacking for Pacific or Atlantic stocks, so that at present we can make little progress in applying the standard techniques illustrated in Fig. 1 without some more work being devoted to parameter estimation.

GROWTH

Although there are indications that ageing from annulations in calcareous structures may be possible (Artüz 1963), preliminary estimates are likely to rely largely on modal analysis (e.g. ENORMSEP Yong and Skillman 1975), bearing in mind that growth and longevity are likely to differ for the two sexes, so that sex should be determined together with any morphometric measurements.

Canadian experience with tagging does not provide much encouragement that this method is cost effective for determining growth, at least for larger fish. Incidental tagging deaths appeared to be high, recaptures low, and there was a difficulty in estimating size at tagging for larger fish. These difficulties can be reduced off S. Florida, where newly-caught, small swordfish may be readily available from the Cuban-American longline fishery. This may also be the best approach and location for determining the extent of stock migrations, since the Florida Strait is relatively close to spawning areas.

Some first parameter estimates for the von Bertalanffy growth equation can be derived from Yabe et al. (1959) for Pacific swordfish stocks, based on seasonal progression of size modes, namely L_∞ = 264 cm, K = 0.124, t_0 = -1.169, (after conversion to fork length[1]). This estimate of L_∞ and growth rate appears low for Atlantic stocks; for example, tentative estimates of L_∞ = 365 cm, K = 0.230 are on file at the St. Andrews Biological Station, based on preliminary ageing from modal progressions and vertebral rings by J. S. Beckett (corresponding rough estimates of sizes at age given in Caddy 1976). It appears from this and other observations (C. Hooker, pers. comm.), that Pacific swordfish growth may be slower, to a smaller asymptotic size, than in the Atlantic.

Noting that for large pelagic fish, estimates of growth rate are in general inversely related to longevity, a rough check on the order of magnitude of K may be offered by the Canadian tagging results. These suggest that swordfish longevity (Tmax) is at least 9 yr, this assuming at least 2 yr to reach commercial (taggable) size and the longest period between tagging and recapture noted to date of 7 yr. Applying the empirical relationship derived by Murphy and Sakagawa (1976) for tunas:

$$K = -0.080 + 2.622\ (1/\mathrm{Tmax})$$

this suggests an estimate for K <0.21. This is intermediate between the two tentative values given above, and lower (as would be expected) than corresponding values obtained for apparently less long-lived marlins (Skillman and Yong 1976). Estimates for these species are:

striped marlin : $K = 0.32 \rightarrow 0.42$;
$L_\infty = 314 \rightarrow 277$ cm;
blue marlin : $K = 0.29 \rightarrow 0.82$;
$L_\infty = 371 \rightarrow 282$ cm.

SIZE AT FIRST CAPTURE

A rough estimate of size at first capture is a prerequisite to application of yield per recruit models. Comparison of commercial size frequencies by longline and harpoon in the mid 1960's (e.g. Beckett and Tibbo 1969 and Table 1) suggests that knife-edge size at first harpoon capture was in the vicinity of 80 lb (36 kg ≡ 155 cm F.L.), and (C. Hooker, pers. comm.) probably slightly lower than this in the Pacific. We may also roughly estimate that size at first capture by longline in the Atlantic was in the vicinity of 10 lb (4.5 kg ≡ 80 cm F.L.).

A more accurate approach to assessing size at recruitment was used employing the cohort analysis method after Jones (1974) with the modification that fishing mortality within equal weight classes rather than length classes was computed, the growth interval between w_t and w_{t+1} (the boundaries of each weight interval) being converted to equivalent length by means of the weight-length relationship in Caddy (1976), before estimating F.Δt, the fishing mortality rate adjusted over a constant time interval. Results of trial estimates with M = 0.2, M/K = 0.87, L_∞ = 365, and starting estimate of E = 0.71 for the largest size group are shown in Fig. 2 for combined data for 1959-60 and 1968-69 respectively, taken from Table 1. These two periods represent periods of almost exclusive harpoon and longline fishing respectively, and from Fig. 2, it is clear that if we assume an asymptote for FΔt around 0.275, then the 50% selection point for 1959-60 is in the vicinity of 180-190 cm F.L., and for 1968-69 is in the vicinity of 110-130 cm F.L., suggesting that the earlier "eye-balled" estimates may underestimate somewhat the size at first capture by both types of gear. Evidently, however, this

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[1] Measurements in Yabe et al. (1959) are from posterior orbit to tail fork, as opposed to fork length (= tip of lower jaw to tail fork) - S. Kume, pers. comm.

analysis should be repeated with better estimates for parameter inputs when available.

ESTIMATION OF OVERALL MORTALITY RATE, Z

Several commonly accepted methods of estimating mortality rate rely on a knowledge of growth parameters and size + age structure of catch, e.g. from Beverton and Holt (1956) overall mortality can be estimated from

$Z = K(L_\infty - \bar{\ell})/(\bar{\ell} - \ell')$ in terms of size at

first capture, (ℓ'), mean size at capture ($\bar{\ell}$), and von Bertalanffy growth parameters. Using the mean size in the catch of 96.6 kg ≡ 210 cm ($\bar{\ell}$) (Caddy 1976) towards the end of the harpoon fishery in 1958, together with the estimated median size at fist capture ($\ell' \simeq 155$ cm), this suggests for the two sets of von Bertalanffy estimates above approximate values of $Z \simeq 0.12 \rightarrow 0.65$. Similarly, towards the end of the longline fishery in 1970 when mean size in the catch was 29.9 kg ≡ 160 cm ($\bar{\ell}$), and median size at first capture ($\ell' \simeq 80$ cm), this suggests corresponding values of $Z = 0.16 \rightarrow 0.59$. One may presume that, in view of the higher Atlantic growth rates, the higher values are more likely to be valid.

Mortality estimates based on rate of decline in numbers caught with time (e.g. variations on the Delury method), are likely to be very sensitive to effects of immigration and emigration from the fishing area, as are most estimates of Z from tagging. In fact, tagging procedures have been used to measure average sojourn time in the fishery (Rothschild 1966) from $(\tilde{Z})^{-1}$, where $\tilde{Z}$ is the rate of population decline from all causes. Both types I and II errors that affect mortality estimates from tagging may be responsible for the unreasonably low estimates of mortality obtained from the limited proportion of Canadian tags returned.

LONGEVITY AND NATURAL MORTALITY

The longevity of swordfish (at least for the females) would appear somewhat greater than for other billfish - recaptures from Canadian taggings have been obtained up to 7 yr after release. This may suggest a relatively low natural mortality rate for the species, at least in the commercial size classes. Better estimates of M may be obtained in one of 3 ways:

1) Catch curves for unexploited populations - (difficult to apply for species with partial spatial segregation of sexes and age groups);

2) Comparison of the relationship between overall mortality and effort at two or more levels of fishing (e.g. Suda's method described in English by Morita 1977);

3) Comparison with estimates for other species. At a first guess, this would suggest a relatively lower value for M, perhaps somewhat greater (say, M = 0.2-0.4 ?) than for an extremely long-lived species such as the bluefin tuna. This type of guess may be somewhat formalized using the relationship between M and K derived for tunas by Murphy and Sakagawa (1976):

$$M = -0.0195 + 1.9388\ (K).$$

Using the above values of K, this corresponds to $M = 0.21 \rightarrow 0.43$, which appears not unreasonable compared with other large pelagic fish where these estimates are available.

FISHING MORTALITY RATE, F

Virtual population or cohort analyses (e.g. Gulland 1965; Pope 1972) usually rely on a known age structure for the population, but this may be inferred given estimates of L_∞ and M/K, an initial guess of exploitation rate (E), and an assumed stable size frequency for the exploited population (Jones 1974). An example of the type of computation is given in Table 2, and could be applied to existing size frequencies, given better estimates of input parameters.

Estimates of exploitation rates from tagging are very sensitive to errors and biases due to tag loss, mortalities on tagging, and emigration. This is illustrated for the Canadian data (Table 3), where J. S. Beckett (pers. comm.) estimated that, of 20 recaptures from 231 fish tagged, only 3/171 (1.8%) were recovered of tagged fish caught on longlines, and 17/60 (28.3%) of those tagged at the surface by harpoon. Solving iteratively for F in the equation:

$$n_t = \frac{F \cdot N_o}{F+M}\left[1-e^{-(F+M)T}\right]$$

over a 7-yr period, provides estimates (all methods combined) of $F = 0.02 \rightarrow 0.06$ ($M = 0.2 \rightarrow 0.4$) which are evidently unrealistically low, and by harpoon tagging alone of $F = 0.1 \rightarrow 0.15$ ($M = 0.2 \rightarrow 0.4$) - still too low to be in accord with other observations from the fishery. It seems likely either that there is a significant mortality on tagging (particularly for longlined fish) or most probably that emigration from the tagging area is occurring (most tag returns were within 400 km of the release points). The method of analysis of Lenarz et al. (1973) may be appropriate here, although existing data are hardly adequate for separate estimation of tagging errors as well as mortality rates.

YIELD/RECRUIT ANALYSIS

As parameter inputs become more refined, yield/recruit analyses can be approached with progressively more rigorous assumptions to give more realistic results. Beginning with a simple knife-edge type of assumption, age-specific catchabilities can be incorporated for a single gear fishery and extended to multi-gear fisheries (e.g. Lenarz and Zweifel 1975). The validity of these more refined analyses depends to a large extent on the reliability of the initial assumptions, and they would seem very premature at this point in our knowledge.

Beverton and Holt (1966) yield tables provide a relatively quick and easy first approximation to the type of predictions possible given some tentative parameter estimates, and may allow the sort of preliminary sensitivity analysis that is likely to be required in the short term until more refined parameters are available.

Using the von Bertalanffy parameter set after Yabe et al. (1959) as an example, a range of M from 0.2-0.4, and the above preliminary estimates of size at first capture, some idea may be gained of the implications of existing harvesting strategies by Atlantic harpoon and longline fisheries in terms of potential yield/recruit, assuming that either gear type is the exclusive method of harvesting the stock.

The yield tables use a modified version of Beverton and Holt's (1957) yield equation:

$$Y' = \frac{W}{R_o W_\infty} = E(1-c)^{M/K} \sum_{n=o}^{3} \left[\frac{U_n \ (1-c)^n}{1 + \frac{nK}{M}(1-E)} \right]$$

where Y = steady state annual yield in weight
R = annual recruitment at age t_r
$R_o = R \cdot e^{M(t_r - t_o)}$, is the number of recruits entering the exploited phase
U_n = summation variable (= 1,-3,+3,-1 for n = 0,1,2,3 respectively)
E = rate of exploitation
c = mean selection length ℓ_c as a fraction of L_∞

Y' is a relative yield function which can be used for directly comparing relative values of ℓ_c and E, if L_∞ and M/K are constant. If these input values differ, yield per recruit at age t_r should be obtained from the following expression:

$$Y/R \cdot W_\infty = Y' \cdot R_o/R$$

before comparing between given sets of input parameters. Thus, for sizes at first capture ℓ_c (L) = 80 cm ℓ_c(H) = 155, the growth estimates after Yabe et al. (1959) yield values of C(H) = 0.587 and C(L) = 0.303, while for the second set of (Atlantic) growth estimates exploitation begins at a relatively earlier point in the life history so that values of C are lower.

Adopting extremes for the range of M and K values as given in Table 4, first estimates of the exploitation rate (Emax) corresponding to the point of maximum yield per recruit (Ymax) as well as the corresponding fishing mortality rates, (Fmax) can be derived.

Some tentative conclusions that can be drawn from this exercise are:

a) rather predictably, yield/recruit will decrease with M for a given size at first capture.

b) For harpoon fisheries, if L_∞ is large, Y(H)max can be attained with reasonable levels of F, for F(H)max of 0.3-0.7. However, if L_∞ is smaller (Pacific estimates), it will only be possible to attain Y(H)max with unreasonably high levels of effort, that is of course, unless the estimate of size at first capture of 155 cm is too high (which may well be the case for Pacific fisheries).

c) For longline fisheries, F(L)max is lower than the fishing mortality rate yielding theoretical maximum yield for harpooning, and Y(L)max may easily be exceeded at high levels of effort. However, if size at first capture is high relative to L_∞ (as in the Atlantic harpoon fishery), the fishing effort providing maximum yield in an exclusively harpoon fishery may be at too high effort levels to be practically attainable.

While conclusions b) and c) are necessarily tentative, given the parameter assumptions, they appear to be borne out by events in the Atlantic swordfish fishery up until 1972. Prior to 1960, landings from the (almost exclusively) harpoon fishery increased continuously with effort, while subsequently, those from the rapidly expanding (and after 1962, almost exclusively longline fishery) dropped off at high levels of effort (Caddy 1976).

PRODUCTION MODELLING

Fitting of catch and effort data by means of the Generalized Production model (Pella and Tomlinson 1969), and/or subsequent models using the same inputs (e.g. Fox 1975), will require consecutively at least 10 independent data points for annual catch and effort, if some sort of equilibrium approximation is to be attempted. Another problem that must be faced in applying this type of approach is the difficulty of intercalibrating effective fishing effort by longline and harpoon, since the two gear types do not necessarily exploit the same age classes (or even, in the N.W. Atlantic, the same sex ratio).

In general, it is believed that yield/recruit models offer a more useful approach for providing management advice in this fishery, at least in the foreseeable future, particularly since a reliable system of collection of effort statistics (e.g. log books) may not be practical under the present "illicit" fishing regime in the western Atlantic.

CONCLUSIONS

Preliminary yield/recruit calculations support the observation that swordfish stocks are relatively more robust to heavy fishing with harpoon than with longline, especially if size at first capture by harpoon is high relative to L_∞. Under these circumstances, while an exclusively harpoon fishery may have trouble attaining the point of maximum potential yield from the population, a longline fishery may easily exceed MSY. At the same time, a longline fishery operating at above the point of MSY, harvesting relatively small fish (Caddy 1976), is probably the best way of minimizing tissue mercury content, since this is linearly related to size (Beckett and Freeman 1974). Simulations of a multi-gear fishery may show the optimal mixture of effort by the two gear types needed to maximize the yield, but this type of approach will have to be postponed until better parameter estimates are available.

SUGGESTED PRIORITIES FOR FUTURE RESEARCH ON SWORDFISH

The following items, roughly in order of priority, appear to require attention in order to improve our understanding of the dynamics of swordfish populations, particularly in the Atlantic area:

1) Estimation of swordfish growth rate by sex. Modal analysis of seasonal size frequencies and closer examination of annular structures in calcareous parts are believed to offer the most promise here.

2) Improved estimates of growth are a necessary precursor to estimating overall mortality rate and, in conjunction with estimates of fishing effort, may allow partition of Z into F and M, if at least two levels of fishing effort are available. (Existing historical data may be of use here.) Cohort analysis using these first estimates of growth and exploitation rate appears to offer most promise.

3) A better understanding of stock boundaries and swordfish migration is a necessary precursor to predictions of sustainable yields and production modelling. There appear to be a number of features of the life history, particularly relating to differential behaviour and distribution of the sexes, that are poorly understood. These may most profitably be tackled by tagging experiments on younger fish, if problems of obtaining tag returns under the current "semi-illicit" fishing regime can be overcome.

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Table 1. Estimated numbers by dressed weight category of Canadian swordfish annual landings, 1959-69 incl., based on total landed weight + port samples of commercial catch.

Dressed wt (lb)	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
<20					36	140	467	346	617	3403	20198
20-39					805	2131	2555	1968	4003	9556	113879
40-59	48		134		2930	6513	3809	2997	7757	9512	80509
60-79	478	126	134	128	3652	6551	6007	4355	9445	1114	90724
80-99	1621		537	352	4340	8517	6383	4917	9496	1120	91955
100-119	3235	1008	1073	1121	5055	8366	6689	5622	8306	8093	74009
120-139	4758	756	1341	2149	6389	7351	5823	6031	6455	5527	55936
140-159	5279	2016	1609	2421	7232	6839	4929	5488	5064	4435	39456
160-179	5217	2016	1074	2680	7900	6739	3840	4337	3818	2940	30124
180-199	4803	2142	2014	2437	7509	6263	3345	3482	3018	2267	24157
200-219	3234	2268	1476	1648	5729	4767	2478	2602	1828	1646	16599
220-239	2527	1134	805	1520	4531	3887	2206	2071	1535	1162	11193
240-259	1954	1260	402	1328	3745	2996	1585	1582	1016	829	9558
260-279	1145	1008	1072	612	2701	2198	1242	1315	736	693	7003
280-299	621	1512	1073	512	1923	1732	1108	947	652	450	5016
300-319	336	630	804	352	1446	1053	689	695	495	292	4062
320-339	479	504	268	272	1153	782	463	425	296	248	2419
340-359	240	504	402	176	770	430	340	289	265	206	1652
360-379	143	378	134	96	750	402	254	238	236	185	1770
380-399	288		134	48	586	230	222	99	188	80	944
400-419	96	126	134	16	345	82	137	89	131	58	1239
420-439	96	126		48	190	81	139	64	148	47	531
440-459			134	48	193	82	70	49	108	30	413
460-479	48	126		16	73		30	20	58	52	295
480-499			134	16	45		69	20	34	6	295
500-519					45		20	4	52	23	236
520-539				16	9		20	4	57	12	177
540+	48				36		20	24	75	12	236

Table 2. Estimate of cohort analysis of swordfish size frequency data by method of Jones (1974) (combined Canadian research longline data for 1958-69, body lengths).

Parameter values assumed: L_∞ : 310-360; M/K: 1.333; M: 0.2-0.6

Length class (cm)	Frequency[a]	0.2						0.4					
		310			360			310			360		
		N_L	F/Z	Z	N_L	F/Z	Z	N_L	F/Z	Z	N_L	F/Z	Z
60-79	7	1083	.06	.21	848	.09	.22	1083	.06	.42	848	.09	.44
		962			767			962			767		
80-99	34		.24	.26		.33	.30		.24	.53		.33	.59
		820			662			820			662		
100-119	44		.31	.29		.40	.34		.31	.58		.40	.67
		677			553			677			553		
120-139	58		.39	.33		.50	.40		.39	.66		.50	.80
		529			438			529			438		
140-159	67		.47	.38		.58	.48		.47	.75		.58	.96
		386			323			386			323		
160-179	64		.51	.41		.63	.54		.51	.82		.63	1.07
		261			221			261			221		
180-199	63		.58	.48		.70	.66		.58	.95		.70	1.32
		152			131			153			131		
200-219	57		.67	.60		.78	.89		.67	1.19		.78	1.79
		67			57			67			57		
220-239	28		.65	.58		.78	.91		.66	1.16		.78	1.82
		24			21			24			21		
240-259	14		.70	.67		.82	1.14		.70	1.34		.82	2.27
		4			4			4			4		
260-279	3		.70			.70			.70			.70	

[a] It is presumed that this analysis will normally be carried out on the calculated size frequency for the annual commercial catch, in order that the estimated population size be meaningful.

Table 3. Number of Canadian swordfish tagged from 1961-1976.

	No. released	Recapture date in years after tagging 1	2	3	4	5	6	7
1961-69	124	1	4	1	2	0	2	0
1970-76	107	6	0	1	0	1	1	1
Total	231	7	4	2	2	1	3	1

Table 4. Preliminary knife edge yield/recruit calculations using tables of Beverton and Holt (1966) and two sets of tentative parameter estimates for growth, natural mortality, and size at first capture.

<u>input values</u>:	L_∞	264	264	365	365
	K	.124	.124	.23	.23
	M	.2	.2	.2	.4
M/K		1.613	3.226	0.870	1.739
nearest approx. in table:		(1.75)	(3.00)	(1.00)	(1.75)
<u>Harpoon</u>					
$l_c(H)$		155	155	155	155
C(H)		.587	.587	.425	.425
E(H)max		0.90	1.0	0.60	0.65
F(H)max		1.80	$\rightarrow \infty$	0.30	0.74
Y'(H)max		0.433	0.145	0.0797	.0373
<u>Longline</u>					
$l_c(L)$		80	80	80	80
C(L)		.303	.303	.219	.219
E(L)max		0.50	0.60	0.50	0.45
F(L)max		0.20	0.60	0.20	0.33
Y'(L)max		.0314	.0129	.0635	.028

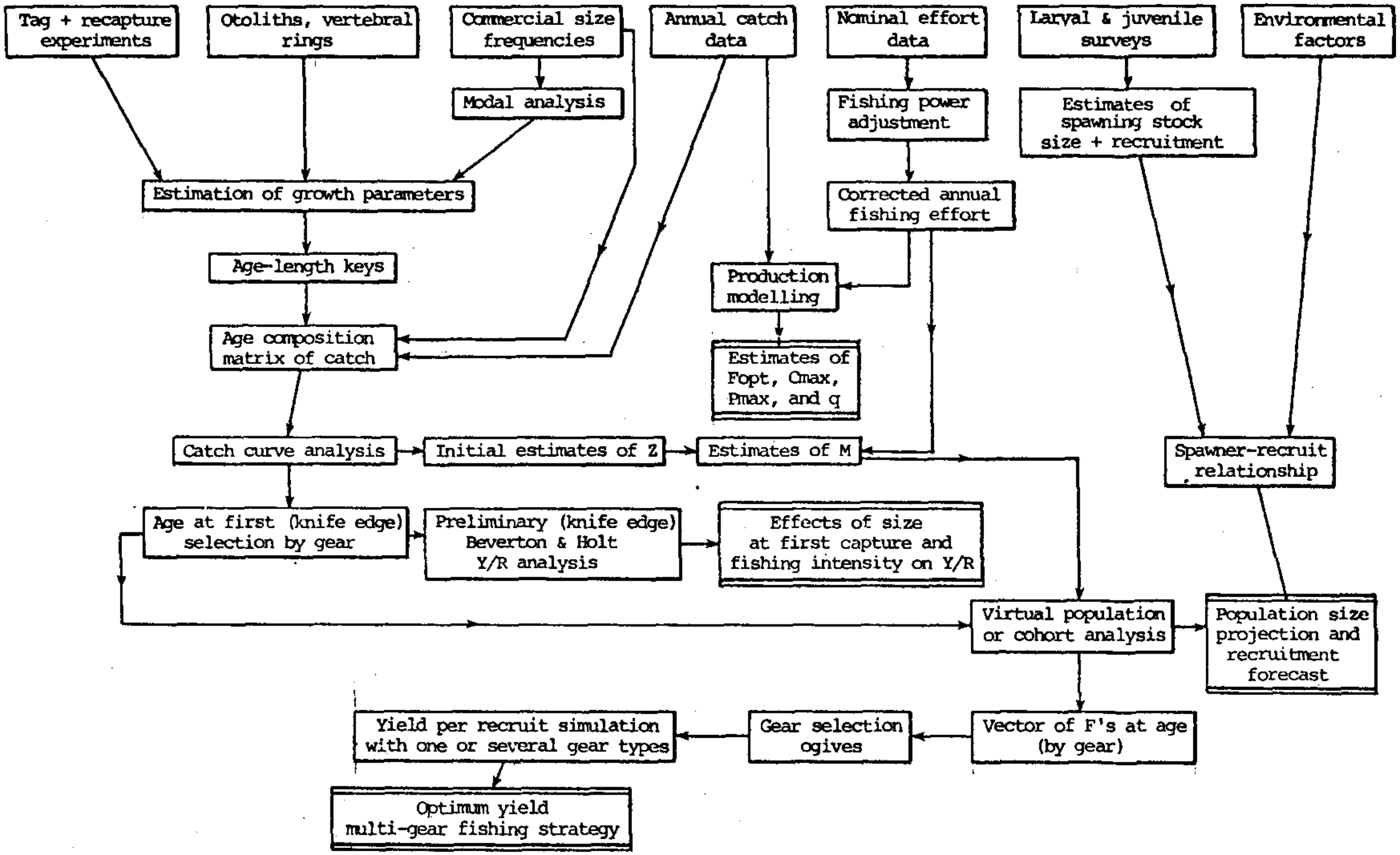

Fig. 1. Idealized sequence of events in estimating population parameters for an exploited fish population.

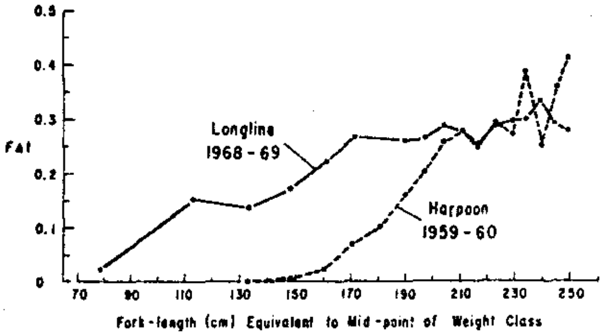

Fig. 2. Analysis of size-specific fishing mortality in the Canadian swordfish fishery during two periods with:

a) predominantly harpoon fishery (1959-60)
b) " longline " (1968-69)

using the method of Jones (1974) on data from Table 1.