Size Frequency Analysis in Stock Assessment - Some Perspectives, Approaches and Problems

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ABSTRACT

Size frequencies may be used in support of fisheries research and management in a number of ways, and this paper presents a non-technical review of some of the more relevant aspects by reference to existing literature. Considerations touched upon include use of length frequency data for estimating growth, mortality and gear selection, as well as broad requirements for data collection, and the subsequent use of the resultant parameter estimates in fisheries management.

Size frequency methodologies are considered in two main categories: dynamic approaches (especially modal analysis) based on samples taken throughout the year, and those that attempt to approximate to equilibrium conditions, for example, by pooling of samples. Some of the limitations of both categories are touched on, for example, with respect to the type of fishing gear used to collect samples, and the types of bias that may result from uncritical use of existing methods of analysis. The use of estimators based on mean size statistics is also briefly discussed.

The procedure for using parameters from size frequency analysis in yield per recruit analysis and production modelling is briefly outlined, as well as an empirical strategy for using size data as an index of the state of the stocks.

INTRODUCTION

There has been a growing appreciation that the size frequency of an exploitable population can provide important information on its population structure, and on the growth, mortality and recruitment processes underlying the observed size "spectrum" in the catch. It has been proposed (Munro, 1983) that this information can supplement, or even in some cases, replace 'conventional' types of fishery data, such as age composition, fishing effort.

This latter proposition is true in some situations, but it has not been clarified what are the constraints, or what would be the components of a system of monitoring and assesment of stocks relying mainly on size frequency analysis. It is also not yet fully resolved which of the growing number of methods in the literature on length frequency analysis should be regarded as "short cut" or "rule of thumb" approaches, and which are suitable for an on-going scientific investigation in support of fishery management.

Some personal opinions are offered here on several of these points, but it is to be hoped that more definitive answers will result from an International Conference on the Theory and Application of Length-based Fish Stock Assessment to be held at the Instituto di Tecnologia della Pesca e del Pescato (ITPP), Mazara del Vallo, Sicily, Italy from 10-15 February 1985. This conference should throw some further light on this subject. My personal pespective, along with that of other workers in the field, is of course liable to change, reflecting this and other fast-moving events in the field of tropical fish stock assessment; however, some key constraints are not likely to be radically modified. At the request of GCFI, it is the author's intention here to provide a non-technical, personal perspective on the use of length frequency data, from parameter estimation to fisheries management, recognizing as far as possible, the potential as well as the limitations of the various approaches suggested in the literature.

SAMPLING REQUIREMENTS

Sampling Frequency

For many tropical fishery resources with relatively shorter life spans (higher natural mortality rates), and higher growth rates than for most similar resources from temperate latitudes, the size frequency of the catch can be expected to change rapidly with time, reflecting the simultaneous impacts of both growth and mortality. Separating these two effects is then one of the key objectives of length frequency analysis. A necessary consequence of this is that although a single representative sample taken at one time of the year may be useful in planning a size frequency sampling campaign, taken in isolation it is unlikely to allow a definitive stock assessment or even definitive estimates of population parameters.

Two basic classes of methods are described in more detail later, but in the first type of method (referred to here as modal analysis), sampling has ideally to be carried out over a relatively short period, so as to achieve a "snapshot" of the size spectrum of the catch over a short period of time, even if successive samples are separated by periods of a month or more.

Pooling samples taken over a significant proportion of the growth season may lead to 'smearing' of the peaks in the distribution due to growth over the sampling period. Thus, in Figure 1, the first mode (A) would, over the second year of life, be progressively reduced in amplitude by mortality, and increased in mean size by growth, to become superimposed on mode B one year later. At best, (Fig. 1), pooling samples over a significant period of time will increase the 'spread' or standard deviation of individual components, and probably will merge some modes that might have been distinguishable with samples taken over shorter intervals. Combining samples taken throughout a whole year (unless year class strength is very variable) should effectively 'smooth out' the distribution, and particularly if seasonal samples are pooled over several years, this may approach the 'steady state' size distributions which form the basis for the second type of analysis discussed later.

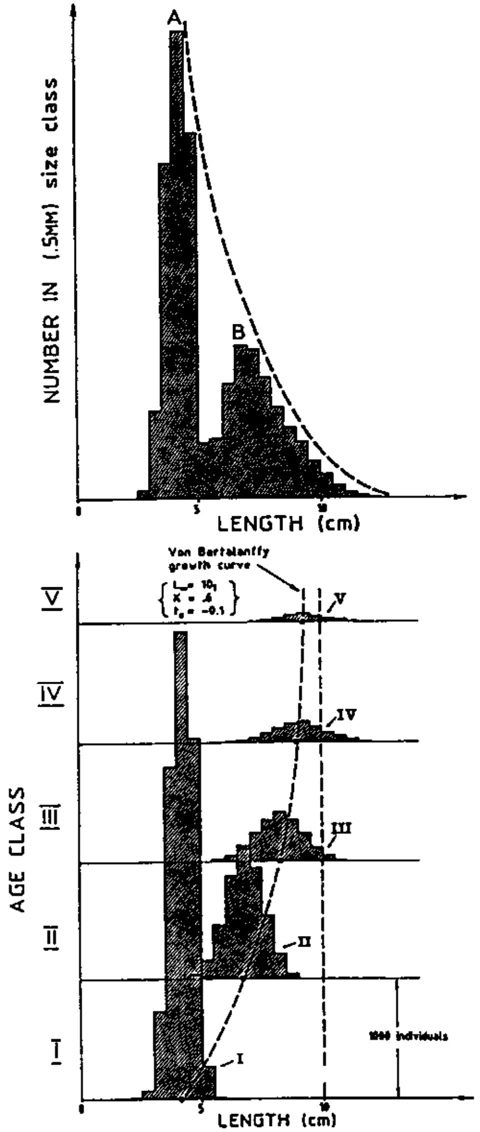

Figure 1. Artificial size frequency generated using an overall mortality rate (Z = 0.8), and initial population of 10,000 individuals at age 1. Mean size at age was defined by a Von Bertalanffy growth curve (K = 0.6, L∞ = 10 cm, t_o = -0.1), with a class interval of 0.5 mm. The individual normal distributions at age (above) were generated by the method in Pauly and Caddy (1985) assuming a ratio (mean:standard deviation 8:1), and summed to give the length frequency distribution below. (Note: age classes of VI+ were not included).

Pre-treatment of Size Frequency Data Prior to Analysis.--Although for certain limited purposes it may be useful to analyze single size frequencies without reference to samples taken at other times, it adds greatly to the value of the analysis particularly for analysis of mortality rates from series of samples, if the proportion they form of the quantity sampled (the total number caught, or the number of the fishable population) can be estimated. The first of these conditions may be fulfilled if commercial catch surveys and/or a log book system on commercial boats are available, and under some circumstances it may be reasonable to assume that catch rate by a standard vessel is proportional to population abundance, thus fulfilling the second condition if size frequencies of the commercial (or research vessel) catch are available.

Combining Size Frequency Data from Different Vessel/Gear Types.--This procedure, often referred to as "weighting up," is necessary in all situations where a variety of gears with different size selection characteristics exploit the same stock, and implies an appropriately designed stratified random sampling scheme which allows the proportion the sampled size frequency makes of the total catch to be determined separately for each vessel and gear type exploiting the stock, and then combined for the time interval represented by the samples.

One approach to "weighting up" that can be used in a situation where fish are landed in unsorted condition in boxes or baskets, is to calculate the total number of individuals caught in each size class, in each period (e.g., a month) based on sampling a group of x boxes of fish chosen at random as follows:

$$\begin{array}{l}\text{Total Catch}\\ \text{of the l'th}\\ \text{size class}\end{array} = \sum_{\begin{array}{l}\text{Vessel}\\ \text{gear type}\\ \text{A=1,2,3. . .N}\end{array}} \left[\begin{array}{l}\text{Mean No. size}\\ \text{class l per box}\\ \text{from vessel type A}\end{array}\right] \left[\begin{array}{l}\text{Mean No.}\\ \text{boxes}\\ \text{landed per}\\ \text{vessel type}\\ \text{A per day}\end{array}\right] \left[\begin{array}{l}\text{Mean No.}\\ \text{days}\\ \text{fished per}\\ \text{vessel type}\\ \text{A in period}\end{array}\right] \left[\begin{array}{l}\text{Mean No.}\\ \text{vessel type}\\ \text{A fishing}\\ \text{in period}\end{array}\right].$$

where the symbol to the right of the equal sign means "add up all products to the right after calculating separately for each vessel gear type." Implied above is a sampling strategy to estimate the values in each of the 4 brackets to the right hand side of the equal sign. Such a sampling scheme would of courses have to be developed in the light of the "mix" of vessel/gear types operating in each fishery.

The total size frequency arrived at by "weighting up" in this fashion is then our best estimate of the total removals from the population in the interval. If a sequence of such samples exists, weighted up to the total catch, these may then be separated into age groups using modal analysis or a length-age key, then fishery mortality rates can be estimated by cohort analysis, or virtual population analysis. Alternatively, after they have been combined over a period of stable fishing, then this "equilibrium size frequency" can be analyzed directly using the Jones (1979) method for cohort analysis on size frequencies.

Weighting Up to Population Abundance.--For several methods of mortality analysis it is desirable that the overall combined size frequency for all gear types is adjusted to reflect the relative numerical abundance of the stock in each time period, as measured for example by the mean number of individuals captured per unit of standard fishing effort.

Sample Size.--Obviously "weighting up" one of several very small samples to the total catch will not give a useful result, however accurately the weighting factor can be estimated, and the actual number sampled (measured) will determine the feasibility of estimating various population parameters from it. No hard and fast rules appear in the literature as to optimum sample size, even though this is the question most frequently asked by those beginning length frequency analysis, and the whole subject of the error structure or variance of various population estimates determined from size frequencies appears yet to have been addressed in a comprehensive fashion (see e.g., Frechette and Parsons, 1983).

Without attempting to theorize on this point, Table 1 provides a short review of statistics from a number of apparently successful size frequency analyses. Looking first at the number of class intervals required per mode, (x is defined here as the number of class intervals separating two successive 'lows' or intermodes), it seems that while in exceptional circumstances, x can be as low as 4, the corresponding sample size needs to be very large 6-7 intervals per mode (in the analyzable portion of the size frequency) seems more conservative, with 30-60 class intervals in the whole size range of sampled population. A sample size of 300-800 individuals per analysis seems of the right order of magnitude.

One other guideline or "rule of thumb" that seems to be generally applied, however, is that if an individual size frequency consisting of say an average of 20-30 individuals per class interval is worth analyzing, it would be much better if this were made up of a number of smaller samples spread over the whole range of boats and gear types fishing at the time, than one large sample from a single boat (see Gulland, 1966).

Size Interval of Measurement.--A compromise has to be sought between measuring fish very accurately and hence slowly, and grouping measurements in small class intervals, so as to be able to distinguish modes or peaks in the size frequency, and measuring a large number of individuals in the same period of time with a coarser unit of measurement and class interval. Obviously, the coarser the unit of measurement, the greater the difficulty of distinguishing successive modes in the size frequency distribution as they approach one another more closely with size.

Again, no hard and fast rule is available, but if modal analysis is the main objective then it should be remembered

Table 1. Statistics from some published studies of modal analysis.

	Pandalus borealis[1]	*Plectropomus leopardus*[2]	Porgy[3]	Pike[4]	Minnow[5]
Number of individuals in analyzed sample	879	319	13,692	523	438
Size range/class interval	17.5 mm/0.3 mm	37 cm/0.5 cm	21 cm/1 cm	60 cm/2 cm	60 mm/2 mm
Number of class intervals in sample	55	72	21	30	29
Maximum number pure modes identified	3	4	4*	5	4
Number of intervals in i.d. size range	50	56	16	30	29
$\bar{x}$ = class intervals/ mode (i.e. size range)	15	14	4	6	7
Method used	NORMSEP	Petersen Method?	Cassie	MacDonald & Pitcher	MacDonald & Pitcher

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[1] (Oct. 77) (Frechette and Parsons, 1983) (carapace length)

[2] Goeden, 1978 (from Pauly, 1983)

[3] East China Sea (from Bhattacharya, 1967)

[4] Heming Lake (MacDonald and Pitcher, 1979)

[5] United Kingdom (MacDonald and Pitcher, 1979)

* Assuming the 5th component is a mixture?

(e.g., Fig. 1) that size frequency is usually considered (for mathematical convenience, and as the basis for most theory of modal analysis) as built up of a number of overlapping individual normal distributions corresponding to age (and sex, if growth differs between males and females; hence the need for separate sampling by sex in this case).

These normal distributions overlap more and more as the maximum theoretical size (L_∞ of the Von Bertalanffy distribution) is approached, when they can be considered to be effectively superimposed (Fig. 1). Thus for a long-lived species, the modal sizes for the older age groups are very close together, and probably will not be separable without extra information such as an age-length key found by analyzing skeletal age structures (e.g., otoliths, scales), if age checks are readable. It is rarely the case that more than 4 modes can be distinguished (or are distinguishable) by modal analysis alone, and most methods of modal analysis require that at least 3 class intervals at the 'peak' of each mode consist of a largely 'pure' sample of the cohort or group of animals in question, with minimal overlap from adjacent cohorts, if separation is to be effected (Table 1). The value of having independent information on size at age (e.g. from otoliths) and needs emphasizing, especially for long-lived species and from tagging (e.g. Jones, 1976) and/or daily growth rings (Brothers _et al_., 1976) for short-lived species.

Clearly, for smaller animals the measurement size interval also needs to be smaller, and it would be wise before embarking on a long-term sampling scheme, to spend some time in experimenting with analyzing samples taken with different size intervals before deciding on a final compromise, bearing in mind that although a relatively small size interval will be time consuming and cumbersome to measure, data can be combined later into wider class intervals, but _not_ vice vera. A very rough rule of thumb from looking at successful analyses in the literature (Table 1) is that there should be roughly 5-6 intervals between successive peaks in the analyzable part of the size spectrum. In this connection, the importance of proper sampling of the smaller sizes (e.g., discards) or even studies involving the use of small mesh gear need emphasizing, given that the likelihood of separating adjacent groups fall off drastically with increasing size.

If the main objective of the sampling is not modal analysis (which is not possible for all species, e.g., those that do not have discrete periods of spawning and recruitment), then as discussed later, length frequency methods requiring "equilibrium" assumptions may still be possible, and the class interval can be significantly larger.

TYPES OF POPULATION ANALYSIS

Methods of size frequency analysis seem to fall into 2 general classes according to the underlying assumptions. Both allow mortality estimates: only the first of these provides simply derived estimates of growth parameters.

Analysis of Dynamic (Seasonal) Length Frequency Samples

Various methods of analyzing single length frequency samples for size modes exist, including "by hand" or graphical methods (e.g., Cassie, 1954), some of which (e.g., Bhattacharya, 1967) have been adapted for use with programmable calculators (e.g., Pauly and Caddy, 1985) or with microcomputers (Sparre, in preparation). Other methods implemented on microcomputers or main frame computers are ELEFAN I (Pauly and David, 1981, now modified by several authors, e.g., Sparre, in preparation), and NORMSEP in FORTRAN (Abramson, 1971), also now in BASIC (Pauly, pers. comm.) and several new methods (e.g., MacDonald and Pitcher, 1979; Schnute and Fournier, 1980; and Fournier and Breen, 1983), which are based on simulation approaches, some of which also provide mortality estimates. All may provide estimates of mean length for each of the separable modal groups as well as numbers of individuals per mode: some (such as NORMSEP) require input of guesses as to mean size at age and variance within each 'pure' age group. Once it is established that modes in the size frequencies can be reliably distinguished, and that these correspond to an identifiable cohort or group of organisms, the process of identifying and following peaks in the size frequency associated with a given sub-group (e.g., an age class or cohort) may then be possible. Sequential modal analysis has a good chance of success for younger age groups and species with short periods of recruitment, and is less likely to be useful for older individuals and species having prolonged periods of spawning and recruitment. (see, however, MacDonald and Pitcher, 1979; and Fournier and Breen, 1983).

Although for long-lived species, a certain amount of information can be obtained from a single sample, it will almost certainly be necessary to have a succession of samples taken through at least one year, so as to follow changes in mean size during the growth season (which may or may not be the whole year; Pauly and Gashutz, 1979). The identified modes should be gradually moving to the right with time allowing the growth rate to be estimated, if pooling of samples over a significant period does not merge adjacent modes: a process that in any case will occur for the older age groups of long-lived species (Fig. 1).

The number of individuals in a given cohort is a sequence of samples may be determined by modal analysis over the size range within which the species is available to the gear or combination of gears without major selection by size, thus allowing an estimate of mortality to be made.

Estimating Growth Rates.--For analysis of growth rates, it is not so essential as for mortality analysis that sample size be related to total catch or abundance, and if a series of (a minimum of 3?) modes can be identified in a single size frequency distribution, a Ford Walford or Gulland plot (Gulland, 1983) can be used to estimate growth parameters (K, L_∞ and t_o) of the Von Bertalanffy equation (Gulland, 1983) and even with 2 modes identified and with a guess of L_∞, a 'forced" Ford Walford plot can be used to give a rough estimate of these parameters (Pauly, 1983).

For short-lived species, fitting growth curves has to rely on identifying and following the same mode through the year at regular intervals. Here, if it is decided to express growth rate K on an annual basis, with continuous growth, the Von Bertalanffy growth curve fitted to monthly modes is given by:

$$l_t = L_\infty \left[1-e^{-K(t-to)/12}\right]$$

and can be fitted as before. Also to be noted here are the methods of Lockwood (1974) and Pauly and Gashutz (1979) which fit a modification of Von Bertalanffy's growth curve to species where seasonal growth is discontinuous - a more common phenomenon in the tropics being the occurrence of a discrete period during which most growth occurs. Plotting the estimated mean size of modes from sequential samples, may allow an erroneously identified mode to be detected: these probably will not lie on a continuous growth curve drawn through the sequence of points for each cohort.

After 1 year of analyzing sequential (dynamic) samples, if more than 1 mode is found per sample, it may be possible to "stretch" the size distribution (referred to as "doubling up" by Pauly), by assuming that mean size at age is the same in the same month in successive years (Fig. 2), in order to obtain a first estimate of growth coefficients. An automatic fitting procedure based on the same principle is embodied in the ELEFAN I program by Pauly and David, 1981. (Note: this procedure cannot be followed for estimating mortality rates: this would give estimates biased by differing annual recruitment in successive years).

Estimating Mortality Rates.--If a cohort (a group of animals born in the same season and year) can then be separated by modal analysis, it may be possible to calculate the total mortality rate for each cohort from:

$$N_{t+\Delta t} = N_t \exp^{-Z\Delta t}$$

here $N_{t+\Delta t}$ are the survivors after time interval Δt (= 1/12 where Δt = 1 year) from an initial population N_t. Better still (e.g., Fig. 4B) estimates of mortality may be obtainable by regression over a series of time intervals (t = 1,2,3. . .) where log catch rate ($\log_e N_t$) declines linearly with elapsed time T:

$$\log_e(N_t) = a-Z\ (T)$$

Some newer methods may provide simultaneous estimates of mortality and growth (see e.g., Fournier and Breen, 1983).

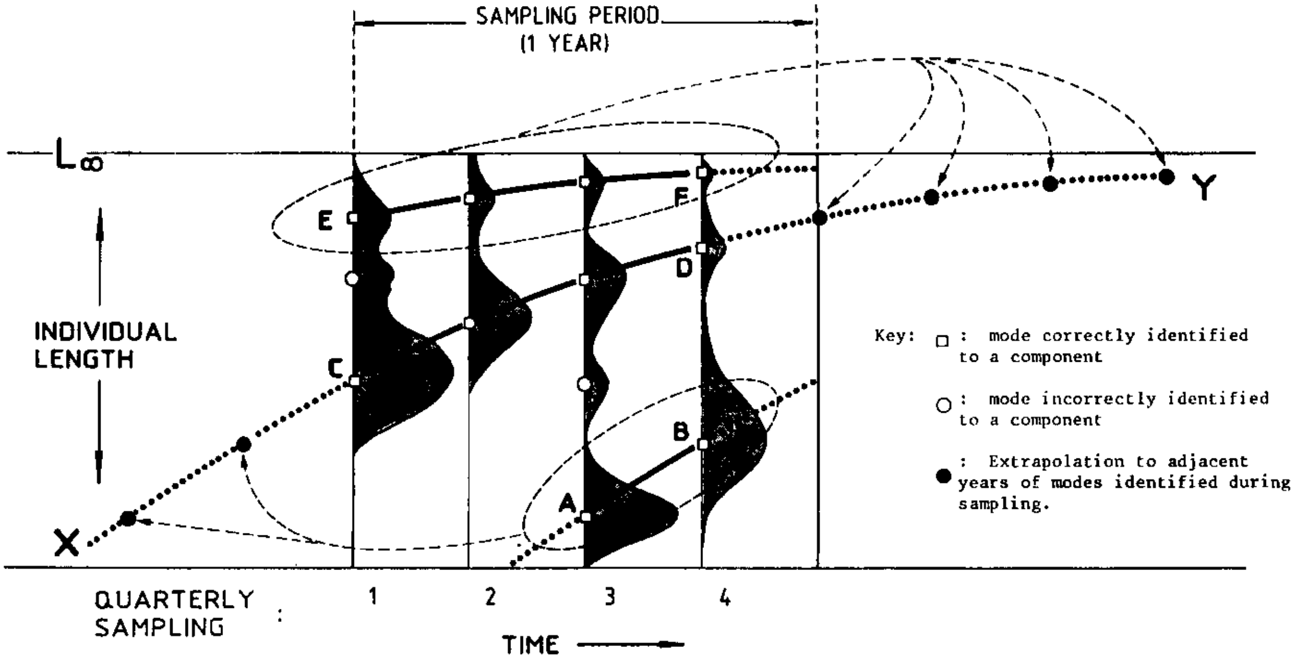

Figure 2. Illustrating in an idealized example, the procedure of 'stretching' or 'doubling up' of a size frequency sampling program in order to obtain preliminary growth estimates after 1 year's sampling. Assuming the same growth characteristics in successive years, the segments A-B, C-D, E-F, are placed in sequence, allowing a fitting of a growth curve to X-Y. Modes whose timing and position appears anomalous with respect to the hypothesized growth curve X-Y are omitted (O) from the fitting.

Analysis of "Equilibrium" Size Frequencies

If you add together samples taken regularly over at least one year (and preferably longer - especially for multi-age species), in a period when fishing effort, growth and recruitment are roughly constant, the individual size modes should largely disappear. A size frequency should then appear whose shape (on the LHS of the distribution) is related mainly to the availability of different size groups, to the size selection properties of the sampling gear, and on the right hand side (Fig. 3), is a function of the ratio of mortality to growth rates (Z/K) in the population. (And for several gear types, also to the size selection properties - see later.)

A typical size frequency of this type produced by an area-swept type of gear (e.g., a trawl) may then have the main characteristic shown in Figure 4 when natural logarithms of the numbers Nl with size (l) are taken.*

Log size frequencies have been used to obtain preliminary estimates by mortality rate (in Caddy, 1977 by moult groups for lobsters), by using a previously-known growth curve to "dissect" the log size frequency: the log numbers between each mean size-at age then being approximately in a ratio determined by the overall mortality rate, Z (remembering that these estimates are going to be progressively less accurate with time after full recruitment).

Length-converted catch curves have been used to estimate mortality rates, especially for short-lived and/or tropical species, and should be restricted in their use to "equilibrium" size frequencies. Figure 5 shows a catch curve based on the simulated "one time" or "snapshot" distribution illustrated in Figure 1; supposedly taken at one time of the year. Here some of the dangers of misinterpretation possible in this type of analysis, especially if not applied to an equilibrium size frequency, are illustrated. Firstly, the line between the 2 question marks in Figure 5 does not represent mortality, but is simply an approximation to the slope of the right-hand side of the parabola resulting from taking logarithms of a "pure" age I normal distribution.

The estimated slope of the regresion line A-A in Figure 5 (Z = 1.1) is also in excess of the true mortality (Z = 0.8) used to create the distribution. This is in part due to the discontinuities in age composition with size at any one time of year, as illustrated in Table 2, which means that the "apparent age" calculated from the Von Bertalanffy growth curve as:

$$t = -\log_e\,(l - l\,t/L_\infty)/K + t_0$$

is in fact a biased measure of the true mean age (as calculated from an age-length key, such as Table 2), especially for young

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* This "log size frequency" can perhaps be referred to as a "catch curve by length," as opposed to the "length-converted catch curve" in Figure 5 where $\log_e$ (number at size/time to growth through the size class) is plotted against the apparent age as predicted by the Von Bertalanffy growth equation.

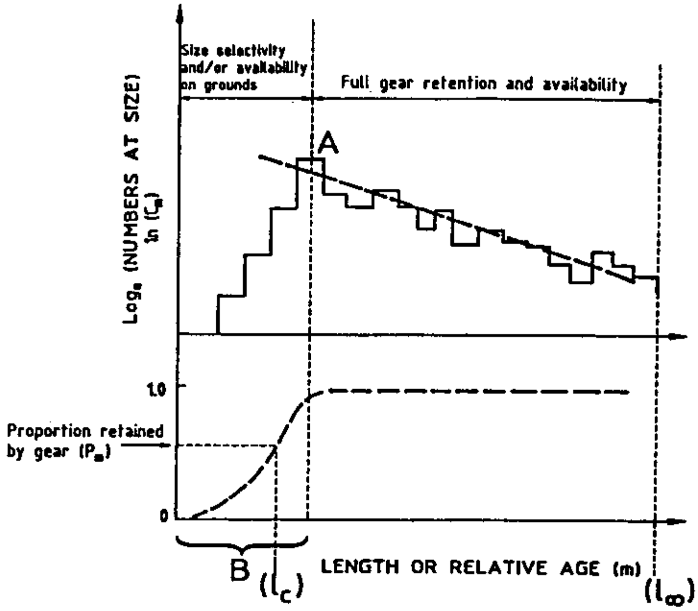

Figure 3. Theoretical configurations of equilibrium size frequencies for different ratios of mortality (Z) and growth rate (K) (from Powell, 1979).

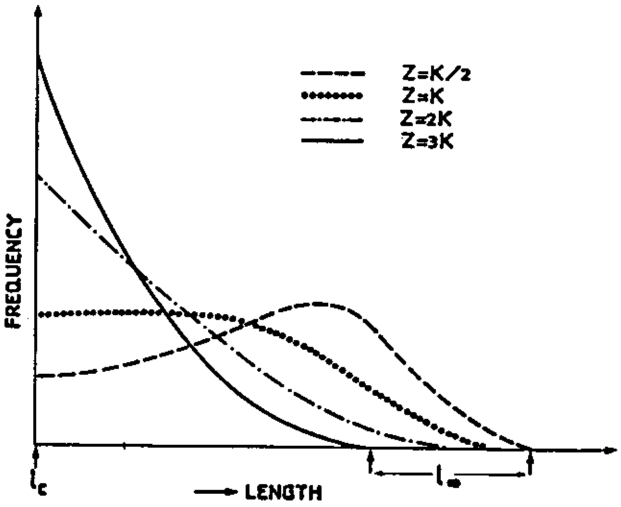

Figure 4. Rationale behind catch curve analysis for area-swept gears, and possibilities for interpretation before and after full size at first retention (A) Z_c = size at 50% retention. B - Size/ages of partial availability to the gear: ignore this segment in estimating Z.

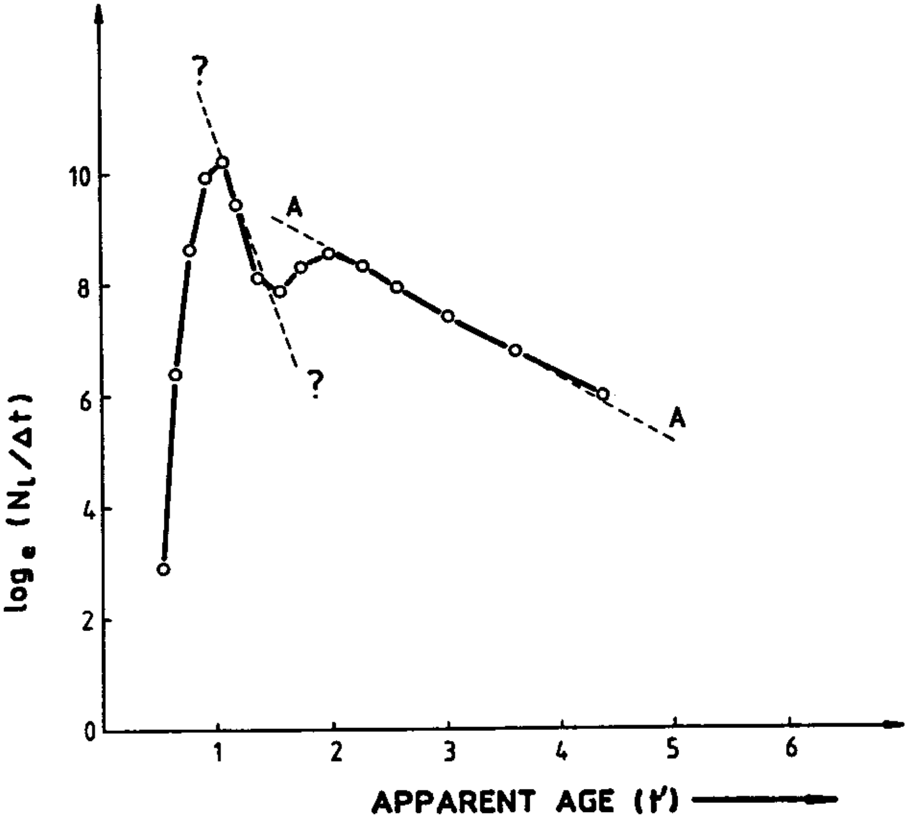

Figure 5. Length-converted catch curve for the data shown in Table 2.

Table 2. Artificial age length key generated by program in Pauly and Caddy (1985) for growth parameters $K = 0.6$, $L_\infty = 10$, $t_0 = -0.1$ with mortality $Z = 0.8$. (Variance of each age group was allowed to increase from S.D. = 0.5 → 1.2 with age). Apparent mean age was calculated from the Von Bertalanffy parameters and true mean age from the age-length key.

Class Midpoint (cm)	Age					Total N_l	"Apparent" mean age ($\bar{t}'$)	"True"* mean age ($\bar{t}$)
	1	2	3	4	5			
2.25	2					2	.52	1.00
2.75	71					71	.64	1.00
3.25	734					734	.76	1.00
3.75	2,803	1				2,804	.88	1.00
4.25	3,939	7				3,946	1.02	1.00
4.75	2,036	42	1			2,079	1.17	1.02
5.25	387	171	4			562	1.34	1.32
5.75	27	473	8	1		519	1.53	1.99
6.25	1	885	55	7	2	950	1.73	2.08
6.75		1,118	131	19	5	1,273	1.97	2.19
7.25		956	244	44	12	1,256	2.25	2.30
7.75		554	355	83	24	1,016	2.59	2.58
8.25		217	403	127	40	787	3.00	2.99
8.75		57	355	159	57	628	3.57	3.34
9.25		10	244	162	67	483	4.42	3.59
9.75		2	131	134	66	333	6.25	3.79
	----(L_∞)----							
10.25			55	90	55	200	--	4.00
10.75			18	49	38	105	--	4.19
11.25			4	22	23	49	--	4.39
11.75			1	8	11	20	--	4.50
12.25				2	5	7	--	4.71
12.75					2	2	--	5.00
13.25					1	1	--	5.00
Totals:	10,000	4,493	2,019	907	408	17,827		

* In fact, an underestimate of true age occurs here, over 6.25 cm, given that age 6+ individuals are omitted.

animals, and those close to L_∞.* One other source of bias in several equilibrium size frequency methods is the effect of changes in variance of size at age with increasing age, which has rarely been explicitly considered.

As for the method of analysis of cumulative size frequencies of Jones and Van Zalinge (1981) illustrated in Figure 6, it is also prudent as for catch curve analysis to base estimates of Z on that straight line section of the catch curve immediately to the right of point A in Figure 4, and to avoid using class intervals close to L_∞.

Gear Selectivity

The left hand side (LHS) of "catch curves by length" (Caddy, 1982) or "length-converted catch curves" (Pauly, 1983) can be used to provide a first estimate of gear selectivity parameters for trawls and other swept area gear. This can be useful in the absence of gear studies, as long as the prerecruited individuals are present on the fishing grounds. The simplest approach to roughly estimating the size at 50% selection, is to draw a line parallel to the linear regression on the RHS of the catch curve,

$$\log_e (N\ \ /2) = a - b(l)$$

and can be fitted by choosing several known pairs of values for N_l and l on the right hand side of the catch curve, and extrapolating the line to meet the LHS of the curve.

Influence of the Type of Fishing Gear Used on the Possibility of Sample Analysis.--The above conclusions and analyses apply particularly to "area swept" gear (trawls, dredges, etc.), where it is reasonable to assume that following full recruitment to the gear, all size groups are represented in proportion to their true abundance. This is probably not true for some other types of gear, e.g., gill nets (Fig. 7).

Gillnets.--Size frequency samples taken with a single mesh size by a gill net (Fig. 7), where a parabola is probably the closest mathematical description of the change in availability with size (Humley, 1975; Pope *et al*., 1975), certainly should not be used for estimating total mortality values from catch curves, and this comment also applies to several other types of fishing gear.

Hooks.--The size selectivity characteristics of hooks, as a method of obtaining size frequency samples, has been little

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* Some bias undoubtedly also results from not including age groups greater than 5 in the analysis of this hypothetical example. Further investigation of these factors is, however, beyond the scope of the present article.

studied. Although smaller fish were taken with smaller hooks within a wide range of hook size, Ralston (1982), concluded that within fairly wide limits, catch rate was insensitive to hook size, and a sigmoid selection curve probably applied, as for trawl gear. This however was not the conclusion of studies of McCracken (1963) or Saetersdal (1963), who found selectivity to depend on hook size. Eggers _et al_. (1982) suggested that since larger fish travel faster, they might be over-represented in samples taken by hook and line _viz a viz_ small fish. Most authors conclude that spatial segregation by sizes on the fishing grounds is more important than hook size _per se_. Clearly, more work needs doing and care should be taken in making too many conclusions on size frequencies, obtained by this method alone.

Fish Traps.--Samples taken with fish traps have been analyzed using length frequency catch curves of the above type, but activity and behavioral interactions of fish of different sizes and species occur in traps in a way that is not well understood at present, particularly for tropical fish traps where the paper by Munro (1974) is one of the few studies available. In addition, although minimum size is dictated by mesh size or lath spacing (e.g., Krouse and Thomas, 1975), maximum size caught will be determined by the diameter of the entry port, and in any case will be heavily influenced by the size range available in the immediate locality of the trap since, as noted above, most fish and invertebrates tend to be spatially segregated by size. As a result, conclusions particularly with respect to the mortality rates of very small and very large specimens (Fig. 7) may be problematical.

Commercial samples taken by handgathering/scuba should be less subject to bias, and here the possibility of detecting bias is also much greater.*

Purse Seines.--Although selectivity through fine-mesh purse seines is probably low, most schooling fish segregate by size, and certain sizes are more commercially acceptable or available than others. As a result, the assumption of constant availability above a given size is also suspect here, as is the assumption that the catch size frequency necessarily represents that for the whole population.

The Influence of Type of Gear on Size Captured

As a general statement, therefore, analysis of mortality rates from catch curves by size of samples taken by lines, traps, gill nets, and purse seines may be problemmatic, or even give misleading results and this may also apply to samples taken by hook and line. This is not to say that the integra-

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* A further discussion of the selectivity and catchability of various types of gear (especially for invertebrates) is given in Caddy (1979).

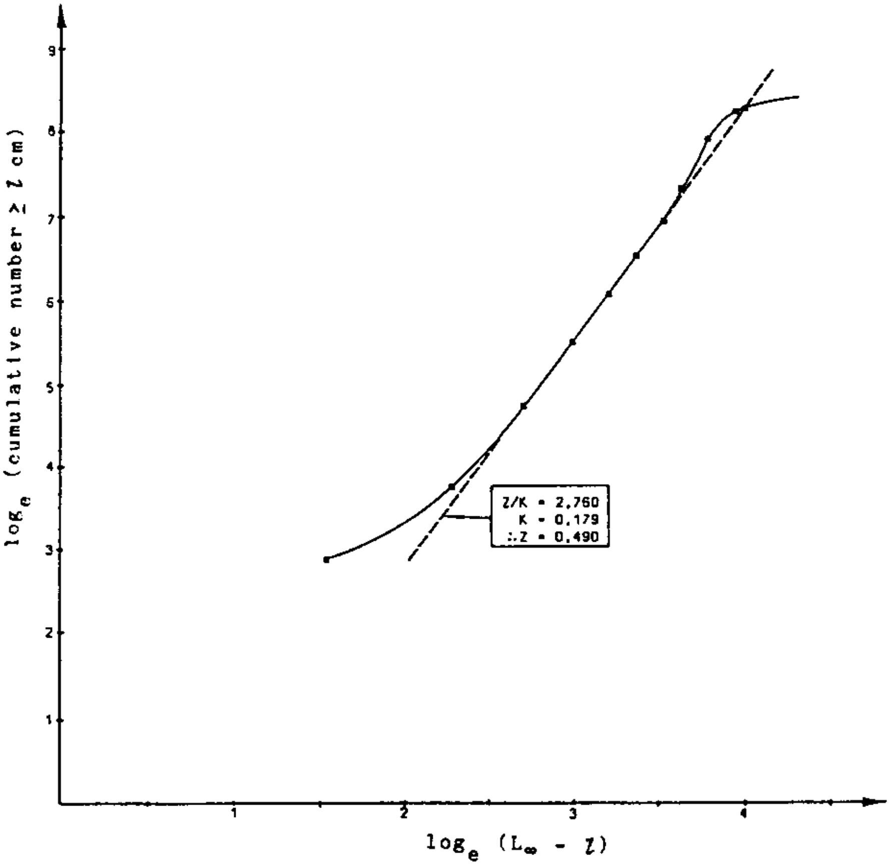

Figure 6. Analysis of cumulative length frequencies for Hake in the Gulf of Lions (CGPM 1982) - method of Jones and Van Zalinge, 1981.

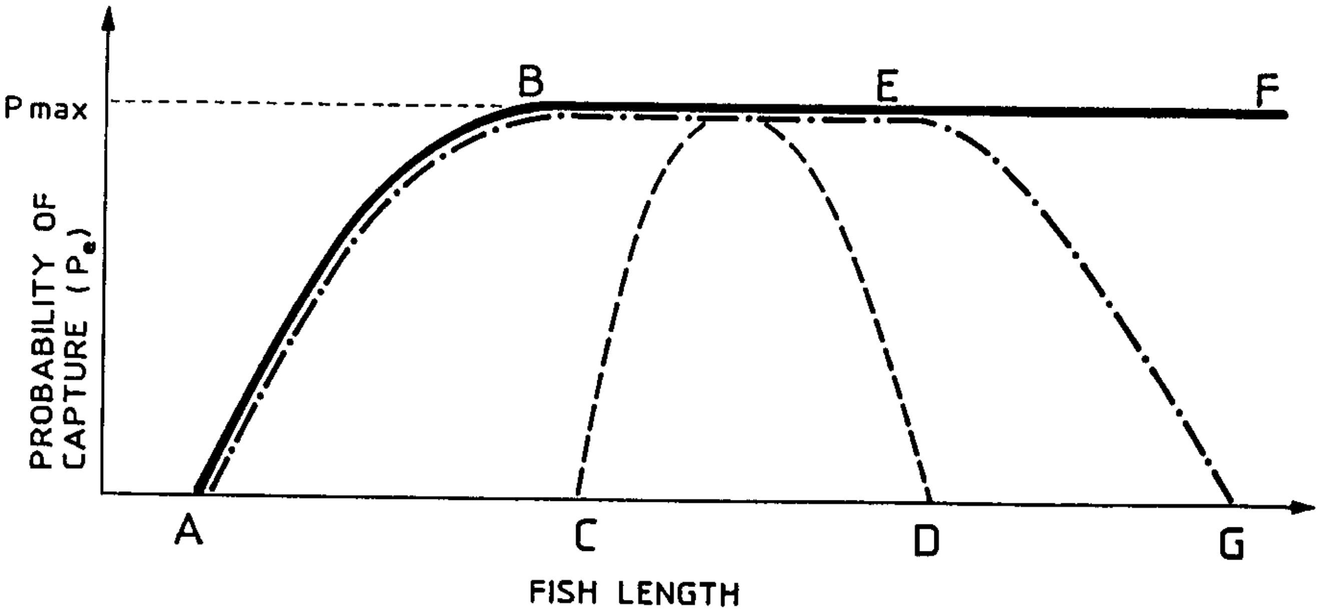

Figure 7. Tentative classification of types of size selectivity curves for various types of fishing gear.
A-B-F: Trawls, dredges (hook and line?)
C-D: Gill nets
A-B-E-G: Fish and lobster traps? hook and line? purse seines?

tion of samples taken using a range of hook sizes or gill net mesh sizes may not overcome these problems, but this is not normally the situation when collecting commercial samples. Analysis of the same samples for growth rate may be possible, but the range of size commonly caught (e.g. in traps, gill nets and seines) may only acommodate a few age modes: at least one of which may have a biased mean size, being only partially retained by the gear (see Jones, 1960; Ricker, 1969).

Clearly, many of the above types of gear are widespread in artisanal fisheries, and are particularly of great importance in the West Central Atlantic, so that although modal analysis based on samples taken using these types of gear may be possible, much care in interpretation will need to be exercised.

Several situations seem possible however, and other methods of analysis of size frequency data collected by these types of gear may still give useful results, as follows:

1) If the value of natural mortality (or at least M/K) and assymptotic size, L_∞ is known, cohort analysis by sizes (Jones, 1981) may be possible to determine relative changes in fishing mortality by size, and to give some idea of the effects of changes in effort and size at first capture on yield/recruit.*

2) Methods based on mean sizes as an index of mortality may also apply (see Beverton and Holt, 1956, and more recent improvements, John Hoenig, pers. comm.), leading to production modelling with mortality rates (see later).

3) Careful research sampling with gears having known, differing, selectivities may give representative samples for analysis.

Estimating Natural Mortality Rates from Size Frequency Data

Assuming that from the methods discussed earlier, a series of mean annual values for Z in succesive years are available, plotting these against the fishing effort expectd in the same year may allow a value of M by Paloheimo's (1961) method (see Ricker, 1975), to be obtained. Alternatively, if two equilibrium periods are known to have occurred with different stable effort levels, Silliman's (1943) method can be used. Under some circumstances, e.g., where Z's by sex are known, it may alo be possible to solve for M's separately by sex (Caddy, 1984). A final alternative is possible if a series of values for numerical yield and Z are known, to obtain an estimate of M by fitting a production curve of yield against total mortality (Csirke and Caddy, 1983). An approach relying solely on a knowledge of environmental temperature and Von Bertalanfy parameters is given in Pauly (1983), and on size at maturity, in Rikhter and Efanov (1976). These give useful indicative

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* Note, however, that errors in cohort analysis increase with natural mortality rate.

values of M, and can be used in the absence of direct estimates, or for comparison.

USE OF PARAMETERS FROM SIZE FREQUENCY ANALYSIS IN THE ASSESSMENT OF STOCKS

Assuming that the methods discussed previously have resulted in estimates being obtained of all or some of the following (all assumed constant):

- Von Bertalanffy growth parameters K, L_∞, t_0
- Overall annual mortality rates Z, or th ratio Z/K
- Natural mortality rate M (or the ratio M/K)
- Size selectivity of the gear (l_c, t_c)

then two main approaches to population analysis may now be possible.

Yield Per Recruit Analysis

Three approaches to yield per recruit analysis are commonly used:

1) Jones Size Cohort Analysis: This may be used as a type of yield per recruit calculation, by varying the input values of size selection (partially recruited F's) and fishing intensity (fully recruited F's) (see Jones, 1979). This in effect allows the impact of changes in size at first capture and fishing effort on the yield per recruit to be determined. Unlike the following methods, 'knife edge' selection assumptions are not necessary with this approach.

2) Yield Tables: This is perhaps the quickest and simplest approach to yield per recruit analysis and requires a knowledge of 3 'composite' parameters:

$$c(= l_c/L_\infty), \ M/K \text{ and } E(=F/Z)$$

in order to allow an index of the yield per recruit for any combination to be read off, or interpolated from the yield per recruit tables of Beverton and Holt (1966).

3) Thompson and Bell Yield per Recruit Analysis: Best described in Ricker (1975), this simple 'bookkeeping' approach is well adapted to either hand calculation, or automatic calculation by computers. Knowing $Z_t = M+F_t$ for each of a series of (short) intervals of duration Δt, the following calculations can be performed in sequence:

- The total number of deaths from all causes in a (possibly arbitrary) initial population N_t at the start of each interval t, is:

$$D_{y=t} = N_t(1-e^{-Z_t \Delta t})$$

- The number of survivors at the start of the next interval by:

$$N_{t+1} = N_t e^{-Z_t \Delta t}$$

- The numbers of deaths caused by fishing is obtained from $C_t = D_t(Z_t - M)/Z_t$
- The yield $Y_t = C_t W_t$ (where W_t is the mean weight of individuals in the catch during t)
- Add up the yield until the population is fished out, or the season finishes.
- Running this above series of calculations through for different series of (monthly, yearly?) values of F_t allows the effects of change in fishing intensity to be determined on yield per recruit (or if total numbers of fish at the start of the season are known), on the overall yield.

Production Modelling

Two approaches to fitting production models with annual Z values (possibly determined from stationary size frequencies) are given in Csirke and Caddy (1983) - the first require annual estimates of Z_t and of total yield (Y_t). These values are plotted (Fig. 1), and the linear regression:

$$Y_t/(Z_t-\text{"M"}) = A-B(Z_t-\text{"M"})$$

fitted for a series of guesses ("M") of natural mortality rate. In some circumstances it may be possible to find a 'best' value of M that maximizes the R^2 for the regression (e.g., Fig. 8; taken from Caddy, in press).

The second approach supposes a series of annual values of Z_t (obtained from size frequencies?) and mean ponderal (weight caught per unit effort) catch rates, U_t. If the linear regression $U_t = a' - b'Z_t$, is linear and significant, this suggests that total production (natural deaths and yield) as a function of Z_t, follows a logistic function. The point at Maximum Biological Production (MBP) (the peak of the parabola of total production) may then be considered a desirable management objective, given that Caddy and Csirke (1983) show that as for the Maximum Economic Yield (MEY), this always occurs to the left of MSY.

Some Possible Errors and Words of Caution

If regarded as extensions of the classical methods of analysis based on a known age structure (see e.g., Beverton and Holt, 1956; Ricker, 1975; Gulland, 1983) size frequency analysis adds a further step to the chain of calculations, namely size → age → growth, and mortality → yield. This

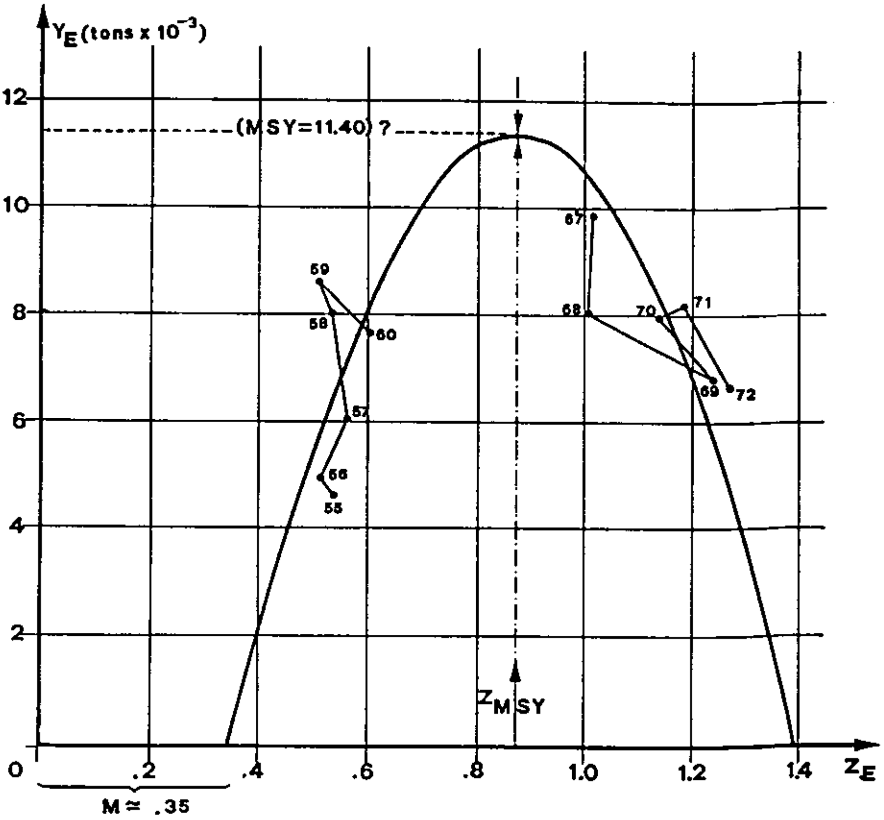

Figure 8. Tentative fitting of logistic model to data from Phillips et al., 1980 - West Australian spiny lobster stock. (Note: the absence of Z values close to MSY undoubtedly has led to an overestimate of MSY).

implies a further loss of precision and various potential sources of error and bias that have not all been fully explored as yet. Most of the methods referred to here, provide simple deterministic estimates of growth and mortality, and some of the potential sources of bias that have been identified are:

Growth

- Younger age groups, partially retained by the sampling gear may show a slightly smaller mean size than for the population as a whole.*
- In the absence of an estimate of L_∞, using only the first few modes to fit a growth curve for longer-lived fish, may overestimate L_∞, and as for the previous point, most sources of error seem likely to underestimate K.
- It should be remembered that in using a linear regression equation to convert from, for example, weight to length (as opposed to from length to weight) the regression equation should ideally be refitted reversing the dependent and independent variables (see however, Bartoo and Parker, 1983, for an improved fitting procedure): (some workeres have advocated the use of functional regression in these circumstances). A similar procedure should ideally be employed when converting from length to age, but this is difficult in the absence of independent information on age composition and hence an age-length key, and constitutes a possible source of bias in several of the methods described in the literature.

Mortality.--The difference between a seasonal and an equilibrium size frequency has been emphasized here, and should be borne in mind in applying some of the approaches in the literature.

- Difficulties in using most methods of analysis of equilibrium size frequencies for the small (partially selected) and large (near to L_∞) size classes suggest that estimates for size groups in the 'middle' size range fully available to the gear should be most reliable (see Table 2).
- It is advisable when using both growth and mortality estimates in yield analysis, to allow for possible errors by employing a range of values around the estimates in question, and it would probably then be prudent to base management decisions on the least favorable of these until better estimate are obtained.

Where periodic marks in otoliths, scales or shells can be related to age, it is advisable to employ these methods, at least for small subsamples, to test the results of modal analysis. This is particularly necessary, where possible, for older individuals.

- If there are significant problems in interpretation of length frequencies because of interference from gear selectivity factors, it would be advisable to look for confirmation

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* This bias would also apply for gears that only capture the smaller individuals of a cohort close to some maximum size at retention.

of population trends from other data sources (e.g. catch and effort analysis). (In any case it is always a good idea to have more than one estimate of the state of the resource).

Optimal Criteria for Management Based on Size Frequency Data

As implied in the immediately preceding section, looking for an effort that immediately provides the maximum sustainable yield (MSY), is now recognized as risky and uneconomic, and some point to the left of MSY on the yield curve is desirable (e.g., 2/3 f_{MSY} Doubleday, 1976). Similarly, for yield per recruit analysis, a fishing mortality rate giving rather less than the maximum yield per recruit (F_{Max}), such as $F_{0.1}$ (Gulland and Boerema, 1973), or Z_{MBP} (Caddy and Csirke, 1983) is usually recommended.

Given that a cautious step-wise approach to effort changes is followed, several methods of analysis, and a variety of control variables can aid the fishery manager in determining population trends. These control variables on the biological side include, size at first capture, mean size, catch rate, total mortality, and of course recruitment. Population trends are often much easier to establish than, for example, the absolute size of the catch or stock or the rate of fishing. Thus, even in the absence of a formal stock assessment, one approach to empirical management, would be to decide in advance on a set of conservative criteria (e.g. a minimum catch rate a minimum mean size in the catch, and a minimum economic return per effort unit), and introduce measures to reduce fishing effort as soon as these arbitary criteria are approached.

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