Chapter 34

Fish stock assessment and management for sustainable fisheries

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INTRODUCTION

The ultimate goal of stock assessment is to devise management systems to mitigate fishery resource depletion. Recent examples of such management regulations in Indian fisheries are implementation of minimum legal size for fish catch, regulations brought out to control length and size of fishing fleet etc. With multi-dimensional expansion of fishing activities in India, it is necessary to analyse stock data critically bringing out suitable recommendations for fishery management.

Fish stock assessment is an evaluation of the state of the stock as relating to changes in the abundance or composition of the stock to changes in the amount of fishing. It involves the use of theories, laws, models and methods propagated by various scientists. There are two general approaches - population model (Schaefer, 1954, 1957) in which the stock is treated as a single entity subject to simple laws of population growth and the analytic approach (Ricker, 1958, 1975) which considers the abundance of the population as determined by the net effect of the growth, reproduction and mortality of individual members of the stock.

Stock assessment gives us the maximum sustainable yield (MSY), fish mortality, the input and output into the fisheries. The various environmental changes as they affect biological and physical features of a fish species, family or the group need to be assessed by using a model for its stock assessment and the basic data is got from research and commercial surveys.

Research survey is a detailed investigation of the fish based on the objectives. It involves taking the data on biological parameters of the fish (length, weight, sex etc), the food of the fish including the percentage composition. Other factors include the environmental features such as time, weather, position of catch, physico-chemical parameters of the water body. Commercial survey involves taking note of basic and important information of commercial usefulness *e.g* length-weight frequencies, percentage composition etc which are strictly for economic purpose.

STOCK STRUCTURE – POPULATION MODEL

The total population can be divided among one to many biological entities, and the numbers-at-age of each entity are tracked over time. Some of these can have unique biology (gender, growth and natural mortality) and some can have a unique season of birth within a year. The total of all entities born within a year is referred to as a year-class or cohort. Each of the biologically or birth season delineated entities will be referred to as a morph. Each morph can be divided into males and females with gender-specific growth and natural mortality rates. In addition, each morph can be sub-divided into slow-, medium- and fast-growing entities termed platoons (Goodyear, 1997).

The population in the initial year can be simply an unfished equilibrium population, a population in equilibrium with an estimated mortality rate that is influenced by data on historical equilibrium catch, or a population that has estimable age-specific deviations from an equilibrium for a user-specified number of the younger ages. Fish of each gender grow according to their current size and current year's growth rate K and asymptotic lengthL_∞. Selectivity is used to define the relationship between the age-length matrix of fish in the population for year y, and the expected numbers at age-length that would occur in a sample from the population using a particular fishery or survey. For fisheries, selectivity also describes how fishing mortality is distributed across ages.

FISH STOCK ASSESSMENT MODELS

There are two main groups of fish stock assessment models:

- holistic, or biomass dynamic models, building on the overall stock as the basic unit where individually based processes such as growth and reproduction are inherently encapsulated in the stock model. The starting point of these models are population abundance indices generated from catch and effort data.
- Analytical models building on individual fish as the basic unit and where dynamic processes such as age, growth, mortality, and maturity are each represented by a sub-model. These models are age- or length structured and deal with a partial or the entire demographic structure of the population. (Baranov, 1918, Thompson and Bell, 1934 and Beverton and Holt, 1957).

Catch per Unit Effor (CPUE) The basic assumption in fisheries theory is that catch (C) and stock abundance, or standing biomass (B) are related by

$$C = q.f.B$$

where f is a measurement of the nominal fishing effort or intensity, and q is the catchability coefficient. This equation can be rewritten in terms of catch per unit effort (CPUE) - which serves as the abundance index –

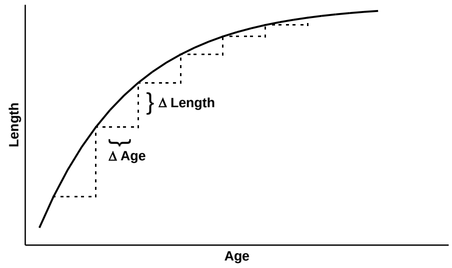
$\frac{C}{f} = CPUE = q.B$.

Growth at length : Measured using length of fish given as L_t (at time t). Population dynamics involves length frequency analysis which are based on the observation that the length composition of a population often exhibits modes (peaks) among the younger age groups. It is furthermore assumed that the growth in length is a random variable (i.e. each individual has its own set of growth parameters; L_∞ - the maximum length of the infinitely old fish called the asymptotic length, K - the growth or curvature parameter and t_0 - theoretical age at L=0 or the initial time if the von Bertalanffy's growth function is adopted), but with the same probability function, i.e. a normal distribution.

The Von Bertlanffy growth function or VBGF is given by

$$L_t = L_\infty(1 - e^{-k(t-t_0)})$$

A Von Bertalanffy Growth Curve



The VBGF parameters can be derived from length frequency analysis.

The basic unit in frequency analysis are the cohorts, i.e. a batch of specimens of approximately the same age that have entered the stock and which by size/age can be discriminated from the rest of the stock.

There are several methods for finding the number of cohorts, their relative contribution, and the mean length of each cohort at different times in one or several composite length frequency distributions:

Visual methods

- The `Petersen` method.
- Modal progression analysis

Petersen method (1892) : It assumes that length at age varies around a single mean value and the fish of the same length have approximately the same age. Then, by simply counting the number of discernible modes and relating these to the respective lengths and frequencies, a rough estimate of the numbers and mean length of each cohort is obtained. Care must be taken that the modes in fact belong to successive age groups and not to dominating cohorts separated by more scarce broods.

Modal Progression Analysis (MPA) : This is based on a series of samples from the same population taken at known time intervals. The method is particularly applicable for short-lived species or for species which show considerable variation in cohort abundance (the method is especially useful with shrimps). When arranging the samples on the same length scale one over the other in successive order and with their relative distances proportional to the time span in sampling sessions, it may be possible to follow the progress of one or several dominant cohorts over length. By measuring or calculating the means, a direct impression of the growth is obtained.

Graphical methods

- Bhattacharya method
- Cassie method
- Tanaka method (parabola method)

Bhattacharya method. This method assume normal distributions of the components in a composite length frequency distribution and transformation of the normal distributions into straight lines. The N, mean and standard deviations are calculation by regression analysis.

This regression is the main element of the Bhattacharya method. When the frequencies in the length intervals (dl) are assumed to be normally distributed, they are regarded as the function values. Then, by the use of the logarithms of the frequencies, computing the difference of two adjacent pairs by subtraction (i.e. (ln(dl+1) –ln(dl)), and by plottings of the difference against the upper limit of dl, a scatter diagram that can be linearised by regression is obtained. The intercept and slope of the regression line will then be an estimate of the corresponding values of the true normal distribution, approximating the frequency distribution. In a composite length frequency distribution with several more or less overlapping normally distributed components, the procedure is to identify and calculate the relative contribution of each component step by step. In other words, one component at a time must be isolated:

1. Find the mean and variance of the first component by the above method
2. Use these figures to calculate the theoretical number of elements in each interval of the first component (this is only necessary in the overlapping length intervals of the first and second component)
3. Subtract these values from the elements in the sample, so the sample now is composed of all parts minus the first component
4. Repeat the whole procedure with the second component (which in fact now has become the 'first')
5. Repeat as long as proper identification of components is possible

The points used for regression are selected on two criteria:

1. Visual inspection of the scatter diagram, identifying those points in the beginning approximating a straight line. This line corresponds to the first normally distributed component, which is interpreted as the N1 cohort.
2. Also an inspection of the slope, the intercept with length axis, and the first and last point used in regression will give an indication of the mean and range of the elements belonging to the examined component, which can be compared to conform with the configuration of the frequency distribution.

Computerised versions

- MAXIMUM-LIKELIHOOD-METHOD- NORMSEP (Tomlinson,1971 , MacDonald and Pitcher, 1979)
- MIX (FORTRAN)
- ELEFAN (Electronic LEngth Frequency Analysis) (Pauly and David,1981)
- LFSA (Length Frequency Stock Assessment) (Sparre ,1987)
- FiSAT (FAO/ICLARM Stock Assessment Tools) (Gayanilo and Pauly 1997) is a package combining ELEFAN and LFSA together with additional features and a more user-friendly interface.

Isometric relation between length and weight of fish :Growth is a process of increase in size or progressive development of an organism. Typically, growth can be defined as the change in size (length, weight) over time. Increment in size is due to conversion of food matter into building mass of the body by the process of nutrition. The length weight relationship is one of the standard methods that yield authentic biological information with two objectives, firstly it establishes the mathematical relationship between the two variables, length and weight, so that to know the variations from the expected weight for the known length groups and secondly this in turn reflects its fitness, general well being, gonad development and suitability of environment of the fish (Le Cren. 1951).

The weight of fish can be denoted in terms of length using the following function (Huxley, 1924):

$W = aL^b$ where 'a' and 'b' are constants.

Mortality : The population contains unique dynamic features such as birth rates, death rates, age structure, phenotypic plasticity, and gene pool. These attributes, which are shaped by the environment (evolution under natural selection) can be collectively summarised under the term life-history traits (Stearns 1976), and their configuration determines the resistance of the population to external disturbance and stress. The survival, mortality rate, fecundity and expectation of life span duration linked to the general environmental conditions. The full set of this information will provide not only a complete description of the population ecology but will, in theory, also enable one to deduce the controlling factors that determine its population dynamics. The key parameters used when describing death are called the mortality rates. The chance of dying as a function of time, i.e. the mortality rate, is, closely correlated to the predictability of the environment, i.e. the frequency of random fluctuations that somehow endangers the survival of the population.

Z is called the instantaneous rate of total mortality, the total mortality coefficient, or simply the total mortality rate. Total mortality Z is F+M which is the sum of natural mortality and fishing mortality. All mortality rates are in units per time, normally per year.

Let N_t denote the number of survivors of a particular cohort during time t. Z is given by the relation $N_t = N_0 e^{-Zt}$ where N_0 is the number alive at t=0. This is the traditional model for describing mortality in a fish stock (fishing or natural causes), the so-called exponential decay model.

Estimation of Z from catch and effort data It is possible to estimate the total average mortality rate when the number of fish in a cohort is available for two different moments in its exploited phase under the assumption that fishing and natural mortality are constant in time for certain (older) age groups.

$$Z_{(t_1,t_2)} = \frac{1}{t_2 - t_1} \ln\left(\frac{N_{t_1}}{N_{t_2}}\right)$$

For the estimation of Z with this formula, it is not necessary to know the absolute values of $N(t_1)$ and $N(t_2)$; only their ratio is required. This permits an estimate, Z, from the CPUE data, since CPUE = q. N_t.

Beverton and Holt's Z-equation based on length data This model, developed by Beverton and Holt (1956), assumes that growth follows the VBGF, that mortality can be represented by negative exponential decay, and that L is estimated from a sample representing a steady-state population.

$Z = K(\frac{L_\infty - \bar{L}}{L - L'})$, where $\bar{L}$ is the mean length of fish of length L' and longer, and L' is "some length for which all fish for that length and longer are under full exploitation".

The natural mortality coefficient, or instantaneous rate of natural mortality (M), is an important, parameter in most mathematical models of fish population dynamics. Normally, all other causes besides fishing are incorporated into this one parameter and is then often assumed to be a constant.

There are three different approaches to estimate M in fish populations (Vetter 1988)

1. Analysis of catch data from commercial fisheries, sampling programmes, or mark and recapture experiments.

2. Correlation with other life history parameters.

3. Estimation of predation from stomach content analysis and consumption experiments.

Pauly's M formula Pauly (1980) made a multiple regression analysis of natural mortality (year) in 175 species on corresponding values of the VBGF parameters K (per year) and L (TL in cm) and the annual average habitat temperature T (1C of the water in which tha stock considered lives), giving the following empirical relationship

$M = 0.8 * e^{-0.0152\ 0.279.\ln(L_\infty) + 0.6543(\ln(\mathrm{K}) + 0.463\ln(\mathrm{T}))}$ where 0.8 is an adjustment factor used for 'schooling species'.

VIRTUAL POPULATION ANALYSIS (VPA)

VPA is an analysis of the catches of commercial fisheries combined with the detailed information on contribution of each cohort to the catch which is obtained through sample programmes and age reading. The idea behind the method is to analyse the catch in order to calculate the population that must have been in the water to produce this catch.

The total landings from a cohort in its lifetime is the first estimate of the numbers of recruits from that cohort. It is however an underestimate as some fish must have died from natural causes. Given an estimate of M, we can do a backwards calculation and find out how many fish belonging to a cohort were alive year by year and ultimately how many recruits there were. At the same time we learn about the fishing mortality coefficient F because we have calculated the numbers alive and know from the beginning how many of them were caught in any particular year.

VPA methods require age-structured data:

- Total catch in number by age and by cohort (usually one per year)

- Estimates of natural mortality (M) by age

In addition, many of the VPA-types of models are incorporating additional information, such as:

- Abundance estimates in absolute terms, each estimate representing one or several age groups (e.g. from acoustic survey abundance estimates)
- Abundance indices, each index representing one or several age groups (e.g. from bottom trawl CPUE from research surveys)
- Effort indices (e.g. effort data from fisheries statistics)
- Mean weight by age and by year corresponding to the catch

While some or all of these elements may not be available, the total catch broken down by demographic structures (age or alternatively lengths) and estimates of natural mortality rates must be present for the VPA methods to be used. Output from VPA methods are:

- Estimates of the (virtual) total population size, stock in numbers (N), by age and by cohort
- Population size at time of capture (tc) used as index of recruitment
- Estimates of the fishing mortality by age (so-called F-array, or fishing pattern)
- Estimates of the catchability coefficient (q) when effort data available
- Estimates of the Spawning Stock Biomass (SSB) when mean weight by age and maturity ogive by age and year are available

Jones' Length Based Cohort Analysis (LBCA)

Jones' Length Based Cohort Analysis (Jones and van Zalinge 1981) is a simple way of decomposing size groups into ages using a growth model (VBGF). In this analysis, the growth is assumed deterministic from the model and the sample is sliced up according to back-transformation of the VBGF (the inverse VBGF) where

$$\Delta t_{L_2-L_1} = \frac{1}{K}\ln\left(\frac{L_\infty - L_1}{L_\infty - L_2}\right)$$

$$N_{i+\Delta t} = N_i . e^{-(F_i+M_i)\Delta t}$$

Given the change in age over each size class (Δt), the population within each size class can be constructed in the same way as a VPA.

LBCA works on a single length frequency sample assuming the population has been in steady state.

- The method is insensitive to errors in the terminal exploitation rate if F>>M
- The model is extremely sensitive to errors in M
- The narrowest length interval that makes data reasonably smooth should be used. Size classes should be chosen such that $M\Delta t \leq 0.3$.
- Considerable care should be taken when only poor growth estimation is available.

PREDICTION MODELS

The knowledge of the past can be used to predict future yields and biomass at different levels of fishing using the prediction models. In other words, these models can be used to forecast the effects of development and management measures such as increases or reduction in fishing fleets, changes in minimum mesh sizes, closed seasons, closed areas, etc. Therefore these models form a direct link between fish stock assessment and fishery resource management.

The first prediction model was built by Thompson and Bell (1934). Beverton and Holt gave the yield-per recruit model for prediction in 1957 which is widely used by researchers.

Yield per recruit (YPR) models are useful to fishery resource managers for predicting the effects of alterations in harvesting activity on the yield available from a given year-class or cohort (Gulland 1983). Two elements that define the model and that are usually regulated by resource managers are fishing mortality (*F*) and the pattern of harvesting activity on different sizes of fish.

Beverton and Holt (1957) noted several important results from the yield per recruit analysis. First is the ratio of the growth parameter (K) to the natural mortality coefficient (M), which estimates the potential of a fish to complete its potential growth before dying of natural mortality.

If M/K is small ($M/K \leq 0.5$), then growth is high relative to mortality, and the cohort will reach maximum biomass at a larger size relative to the maximum size, or the stock (in the absence of fishing) will contain relatively larger fish. From a fishery perspective, management should maximize the size or age of entry to the fishery with only light fishing mortality on smaller fish. If M/K is large ($M/K \geq 2.\ 0$), then natural mortality exceeds growth, indicating many fish will die before completing their potential growth. Again, from a fishery perspective, management should allow heavy fishing with a small size (age) at first capture, so as to harvest the maximum biomass before they die of natural causes.

Further reading:

Baranov, F.I.(1918) On the question of biological basis of fisheries. *Nauchen. Issled. Ikhtiol. Inst. Izv.*, **1**: 81-128 (in Russian).

Beverton, R.J.H. and Holt, S.J.(1956) A review of methods for estimating mortality rates in exploited fish populations with special reference to sources of bias in catch sampling. *Rapp. P. –v Reun, CIEM*, **140** :67-83.

Beverton, R.J.H. and Holt, S.J.(1957) On the dynamics of exploited populations. *Fish. Invest. Minist. Agric. Fish. Food. G.B. (2 Sea Fish),* **19** : 533p.

Gayanilo, F.C. Jr. and Pauly, D. (eds.). (1997) FAO-ICLARM Stock Assessment tools. (FiSAT). Reference manual. FAO Comp. Inf. Ser. (Fish.). No. 8. FAO, Rome, 262 pp.

Gulland, J. A. (1983) Fish stock assessment: a manual of basic methods. John Wiley & Sons, New York. 223 pp.

Huxley, J. S. (1924) Constant differential growth-ratios and their significance. *Nature*, **114**: 895-896.

Jones, R. and van Zalinge, N.P. (1981) Estimates of mortality rates and population size for shrimp in Kuwait waters. *Kuwait Bull. Mar. Sci.,***2:**273-288.

Le Cren E D. (1951) The length-weight relationship and seasonal cycle in gonad weight and condition in the perch *(Perca fluviatilis). J. Anim. Ecol.* **20**:201-19.

MacDonald, P.D.M. and Pitcher, T.J. (1979) Age groups from size frequency data : a versatile and efficient method of analysing distribution mixtures. *J. Fish. Board. Can.,* **36** : 987-1001.

Pauly, D. (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J. Cons. CIEM*. **39(2**): 175-192.

Pauly, D. and David, N. (1981) ELEFAN 1, a BASIC program for the objective extraction of growth parameters from length-frequency data. *Meeresforsch,* **28** : 205-211.

Ricker, W.E. (1954) Stock and recruitment. *J. Fish. Res. Bd. Can.***11**: 559-623.

Ricker, W. E. (1975) Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada***191**: 382 pp.

Schaefer, M.B. (1954) Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Bull. Inter-Amer. Trop. Tuna Commission***1**: 27-56.

Schaefer, M. B. (1957) A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical Pacific Ocean. *Inter-Am. Trop. Tuna Comm. Bull.* **2**: 247-285.

Sparre, P. (1987) FAO package of computer programs for fish stock assessment. *FAO Fish. Tech. Pap. 101, suppl. 2.* FAO, Rome.

Stearns, S.C. (1976) Life-History Tactics: A Review of the Ideas. *Q. Rev. Biol.***51**: 3-47.

Thompson, W.F. and F.H. Bell, (1934) Biological statistics of the Pacific halibut fishery - Effects of changes in intensity upon total yield and yield per unit of gear. *Rep. Int. Fish. (Pasific halibut) Comm.* **8**. 49 p.

Tomlinson, P.K. (1971) NORMSEP: Normal distribution separation. In Abramson, N.J. (ed.), Computer programs for fish stock assessment. *FAO Fish. Tech. Pap. No 101.* FAO, Rome.

Vetter, E.F. (1988) Estimation of natural mortality in fish stocks: A review. *Fishery Bulletin*, **86**: 25-43.