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A Review of assessment tools for data-limited fisheries

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Abstract

One of the precautionary management approaches is to set up a pair of reference points, a target reference point (TRP) and a limit reference point (LRP). An TRP indicates the exploitation target and an LRP defines the limit, toward which management strives. TRPs and LRPs are formulated through technical analysis. This paper describes various empirical equations and fisheries assessment models which can be used to derive reference points. The emphasis was put on the data requirements and procedures for fitting models and estimating parameters. Assumptions involved in the models are described. The bootstrapping and Monte Carlo simulation techniques, and Bayesian analysis, are also illustrated.

Résumé

L’une des démarches de gestion prudente consiste à établir une paire de points de référence : un point de référence cible (« TRP ») et un point de référence limite (« LRP »). Le « TRP » est l’objectif d’exploitation et le « LRP » est la valeur limite que tend à atteindre la gestion. Ces deux points sont établis par analyse technique. Le document présente diverses équations empiriques et modèles d’évaluation des pêches pouvant servir au calcul des points de référence. L’accent est mis sur les données et procédures nécessaires à l’ajustement des modèles et à l’estimation des paramètres. Les hypothèses utilisées pour les modèles sont décrites et on illustre des techniques de simulation par méthodes « bootstrap » et Monte Carlo ainsi que des analyses bayesiennes.

1. Introduction

A framework for provision of scientific advice for the management of new and developing marine invertebrate fisheries has been developed (Perry et. al. 1999). This framework explicitly endorses the precautionary approach for fisheries management and research, as advocated by Garcia (1994), FAO (1995a) and FAO (1996), due to the very nature of fisheries resources, which are highly variable, poorly controllable and slowly reversible. The past few years have seen a major proliferation of action on the development of Reference Points (RPs) to achieve precautionary fishery management goals, as traditional management approaches based on target reference points alone have proved vulnerable to overfishing.

A Reference Point is defined as a conventional value, derived from technical analysis, which are believed to be useful for the management of the unit stock (Caddy and Mahon 1995). FAO (1995b) and Caddy and Mahon (1995) put forward the concept of using a pair of RPs, Target Reference Point (TRP) and Limit Reference Point (LRP), to manage fisheries stocks in a precautionary manner. A TRP indicates a state of fishing which is considered to be desirable and at which management action should aim. A LRP indicates a state of a fishery which is considered undesirable and which management action should avoid. When LRP is approached, measures should be taken to ensure that it will not be exceeded. If it is exceeded, immediate action is needed, such as a substantial reduction in fishing effort or even closure of the fishery for a period of time.

Values of RPs are often derived from assessment models. When data are not sufficient, simple empirical calculations may be employed. Fishing mortality (or fishing effort), stock biomass and yield are the most basic Reference Variables for formation of RPs.

In this paper, I describe how to use different assessment models and empirical equations to derive RPs (Table 1). Emphasis was put on the data requirements, fitting procedures, advantages, limitations and assumptions of these models. To help readers assess the bias in parameter estimates, the bootstrapping and Monte Carlo simulation techniques, and Bayesian analysis, are described.

2. Empirical Equations

When biological and fisheries data are limited, empirical equations may be used to formulate RPs (Table 1).

2.1. Annual Yield Estimation

When the only information available is commercial catches and estimates of stock biomass (or biomass indices), the so-called "Maguson-Stefanson feedback gain rule" may be used to set quotas (Caddy 1998). It is reported to be particularly useful when a stock has been gradually declining in size over time and needs to be restored from the depleted to the productive condition (Caddy 1998).

$$Y_t = Y_{t-1}\left(1 + \frac{g(B_{t-1} - B_{t-2})}{B_{t-2}}\right) \qquad 2.1$$

where Y is catch and B is biomass or a biomass index such as CPUE, t is year and g is referred to as the 'feedback gain' and reflects the degree of proportionality between changes in biomass for the past two years. The value of g is set arbitrarily. When the stock is decreasing gradually, values for g of one or greater seem to contribute to precautionary approaches in simulations (Caddy 1998).

2.2. Maximum Constant Yield Estimation

In New Zealand, several yield-based reference points are frequently used in fisheries management. Maximum Constant Yield (MCY) is defined as the maximum constant catch that is estimated to be sustainable, with an acceptable level of risk, at all probable future levels of biomass (Annala 1993). An acceptable level of risk is open for specific definition. For instance, Francis (1993) defines it as the spawning stock biomass above 20% of its virgin level at least 90% of the time. MCY corresponds to a relatively low level of harvest and may be regarded as a precautionary target (Caddy 1998). There are four methods used in data limited situations in New Zealand to calculate MCY (Annala 1993).

2.2.1. For a developing fishery

$$MCY = 0.25F_{0.1}B_0 \qquad 2.2$$

where B_0 is the unfished biomass, $F_{0.1}$ is a fishing mortality rate at which the marginal increase in yield per recruit is 1/10 of the marginal increase at a very low value of fishing mortality. If $F_{0.1}$ is unknown, the natural mortality rate, M, may be used instead.

2.2.2. For a developed fishery with historic estimated biomass

$$MCY = 0.5F_{0.1}B_{av} \qquad 2.3$$

where B_{av} is the average historic recruited biomass. If $F_{0.1}$ is unknown, M may be used instead.

2.2.3. A developed fishery with an MSY estimate

$$MCY = \frac{2}{3} MSY \qquad 2.4$$

where *MSY* is the maximum sustainable yield, usually derived from biomass production modelling.

2.2.4. A fishery with catch data and effort information

$$MCY = cY_{av} \qquad 2.5$$

where *c* the natural variability factor, which depends on natural mortality, M, and ranges between 0.6 and 1.0, Y_{av} is the average catch over an appropriate time period. Ideally in this period, there should be no large change in fish effort (or mortality), in quotas, and in catch. This period should be half the exploited life span.

This empirical approach is useful, when only qualitative evaluation of fishing effort is available and production modelling can not be used. It also comes handy, when quantitative fishing effort data are present, but critical assumptions of production models have been violated and production modelling should not be used.

2.3. Estimation of upper limit for total mortality rate

Clark (1991) showed that if recruitment to the fishery takes place much later than maturation, the maximum sustainable fishing mortality, F, can be significantly higher than $F_{0.1}$ without dangerously reducing the spawning biomasss, and if recruitment takes place much earlier than maturation, a truly sustainable F may be much smaller than $F_{0.1}$. Thus, ideally we should allow fish to spawn at least once, on average, before catching them. Die and Caddy (1997) suggested a way of using an upper limit of total mortality rate or a minimum size at first capture in this respect of management approach. Suppose that L_m is the length of fish in the stock, half of which is mature and $\overline{L}$ is the average length of fish in the catch. If $\overline{L} > L_m$, the stock is more likely to be able to sustain itself than if $\overline{L} < L_m$. Beverton and Holt (1957) provided a method to calculate the total mortality, Z, based on the average size of fish in the catch, if the growth can be modelled by the von Bertalanffy equation:

$$Z = K \frac{L_\infty - \overline{L}}{\overline{L} - L_c} \qquad 2.6$$

where $\overline{L}$ is the mean length of all fish, L_c is the length at first capture. When incorporating the inequality $\overline{L} > L_m$, the following inequality equation is obtained:

$$Z < Z^* = K \frac{L_\infty - L_m}{L_m - L_c} \qquad 2.7$$

where Z^* is the upper limit of total mortality rate, when the condition, $\overline{L} > L_m$, is met. If $L_m < L_c$, there is no need of applying this equation, and the fishery stands a good chance to sustain itself, as, on average, a fish will spawn, at least, once before being caught.

Equation 2.7 provides, in the absence of information on the stock-recruitment relationship, a simple way to check the effects of fishing on the spawning stock. Z^* may serve as a LRP. Equation 2.8 can be used to establish the minimum size at first capture required to support a fishery where $\overline{L} > L_m$:

$$L_c > L_m - K \frac{L_\infty - L_m}{M} \qquad 2.8$$

where M is the natural mortality rate. This equation is only defined if

$$\frac{L_\infty}{L_m} > \frac{M}{K} + 1 \qquad 2.9$$

2.4. MSY estimation

Gulland (1971) proposed the following equation to calculate MSY, when the unfished stock biomass, B_∞ ,and natural mortality rate, M, are known:

$$MSY = xMB_\infty \qquad 2.10$$

where x is a constant that may be related to the growth and mortality characteristics of the stock. Gulland (1971) suggested that x may be set as 0.5. This is equivalent to setting fishing mortality equal to M based on the logistic growth model. It is now well known that to set x to be 0.5 is too risky. Beddington and Cooke (1983) showed that x lay typically in the region of 0.3 and decreases as M increases. Garcia et. al. (1989) recommended $x = 0.2$. After examining the Gulland approximation for a large number of stocks of small pelagic fish with high natural mortality rates, Patterson (1992) noted that $x >= 0.33$ consistently caused stocks to decline, while $x <= 0.25$ have generally allowed stocks to increase in size. Thus, *MSY* calculated by setting x to be 0.2-0.3 may be used as a TRP and this is basically the same as equation 2.2.

3. Biomass Production Models

Biomass production models are among the simplest and most widely used approaches in the assessment of exploited fish populations due to the readiness of catch and effort data, without having to know ageing or stock and recruitment relationship (Table 1). The primary parameters to be estimated from fitting a production model are MSY and E_{msy}. MSY is regarded as a maximum sustainable yield, a maximum catch that may be taken from a stock without affecting the stock production or the catch of future years. E_{msy} is the fishing effort corresponding to MSY. It has been widely used as a TRP for fisheries around the world. However, previous experience in fishery management has cast doubts on the usefulness of MSY as a safe TRP (e,g, Larkin 1977). A constant MSY is not a reality in most fisheries, as stock sizes vary with the strength of year classes. However, MSY may still serve as an LRP, possibly with some reduction so as to take account of uncertainties in the input data and model parameter estimates.

To obtain MSY and E_{msy}, production models are usually required. The most commonly used is the Schaeffer (1954) model, which assumes a logistic growth function:

$$\frac{dB}{dt} = rB(1 - \frac{B}{B_\infty}) \qquad 3.1$$

where B is the stock biomass, r is an intrinsic rate of population growth, B_∞ is the unfished equilibrium stock size, and $\frac{dB}{dt}$ is the biomass production per unit time.

Its main feature is the symmetric relationship between surplus production and biomass. Surplus production is largest at half of the virgin stock size. Surplus production decreases to zero as the stock size increases to B_∞ or decreases to zero.

In an exploited stock, biomass production is described as:

$$\frac{dB}{dt} = rB(1 - \frac{B}{B_\infty}) - C \qquad 3.2$$

where C is the catch per unit time. Catch is assumed to be proportional to the stock biomass (B) and fishing effort (E):

$$C = qEB \qquad 3.3$$

where q is the catchability coefficient (proportion of the stock biomass caught by one average fishing effort). Catch per unit effort (U) is thus an index of the biomass:

$$U = \frac{C}{E} = qB \qquad 3.4$$

There are generally three ways of estimating parameters of the production model: the equilibrium method, process-error method and observation-error method. Reliable parameter estimates require a good contrast in effort and catch data.

3.1. Equilibrium method

This method has been widely described in the literature (e.g. Gulland 1983, Quinn and Deriso 1999). At equilibrium, the surplus production, $\frac{dB}{dt}$, equals zero, and the relationship between the catch per unit effort (U) and fishing effort (E) is:

$$U = U_\infty - U_\infty \frac{q}{r} E \qquad 3.5$$

where U_∞ is the catch per unit effort, when the biomass is equal to the biomass at the unfished state. Equation 3.5 conforms to a simple linear model:

$$U = a + bE \qquad 3.6$$

where a = U_∞ and b = $-U_\infty \frac{q}{r}$. Multiplying fishing effort on both sides:

$$C = aE + bE^2 \qquad 3.7$$

where C is the catch. This model suggests that the equilibrium yield is related to fishing effort by a symmetrical parabola. The parameters, a and b, are estimated by fitting a simple linear model with fishing effort as the independent variable and catch per unit effort as the dependent variable. The values of a and b are then substituted into equation 3.7 to construct the parabolic curve, from which E_{msy} can be estimated:

$$E_{msy} = -\frac{a}{2b} \qquad 3.8$$

Substitute E_{msy} into equation 3.7 to get MSY:

$$MSY = -\frac{a^2}{4b} \qquad 3.9$$

Gulland (1961) suggested using an average effort, instead of individual effort, over the last n years, where n is the number of age classes being fished.

This method relies fundamentally on the assumption that the stock is at equilibrium, at which annual yield is equal to the surplus production of the stock. This is rarely the case, if ever true. The consequence of using this equilibrium method is that surplus production and fishing effort are usually overestimates, when data are gathered during a stock decline, for instance, during fishery development (Hilborn and Walters 1992). However, Caddy (1996) believes that the equilibrium method still has its own use. It could be used to represent the average long-term behaviour of the system and to estimate LRPs to be used in a precautionary fashion.

3.2. Process-error methods

These methods do not require the equilibrium assumption.

3.2.1. Schnute's non-equilibrium method

Schnute (1977) showed that the Schaefer model could be transferred into the following dynamic equation:

$$\ln\frac{U_{t+1}}{U_t} = r - \frac{r}{B_\infty q}(\frac{U_{t+1}+U_t}{2}) - q(\frac{E_{t+1}+E_t}{2}) \qquad 3.10$$

This is a form of a multiple linear regression with two independent variables, X_1 and X_2:

$$Y = a + bX_1 + cX_2 \qquad 3.11$$

where $Y = \ln\frac{U_{t+1}}{U_t}$, $X_1 = \frac{U_{t+1}+U_t}{2}$, and $X_2 = \frac{E_{t+1}+E_t}{2}$. Parameters, *a*, *b* and *c*, can be estimated by using multiple linear regression method with an assumption of additive random error. Estimates of primary surplus production parameters are obtained as follows:

$$q = -c$$

$$r = a$$

$$B_\infty = \frac{a}{bc}$$

$$MSY = \frac{rB_\infty}{4}$$

$$E_{msy} = \frac{r}{2q}$$

3.2.2. Walters and Hilborn's difference method

Walters and Hilborn (1976) suggested a simple difference equation of the Schaefer model:

$$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{B_\infty}) - C_t \qquad 3.12$$

where B_t is the biomass at time *t*, and other parameters have the same meanings as in the Schaeffer model. Based on this model, they derived a multiple linear regression (see Hilborn and Walters (1992)):

$$\frac{U_{t+1}}{U_t} - 1 = r - \frac{r}{B_\infty q}U_t - qE_t \qquad 3.13$$

where U_t and E_t are two independent variables and $\frac{U_{t+1}}{U_t} - 1$ is the dependent variable.

After estimates of *r*, *q* and B_∞, the primary parameters can be calculated as:

$$MSY = \frac{rB_\infty}{4} \qquad 3.14$$

$$E_{msy} = \frac{r}{2q} \qquad 3.15$$

Uhler (1980) used Monte Carlo simulation and showed that the Schnute non-equilibrium model performs better than this one.

3.2.3. Observation-error method

No equilibrium assumption is required in using this method either. The basic idea is to take initial guesses of r, q, B_∞ and to make time-series predictions of the biomass and catch per unit effort by using the following two equations:

$$\hat{B}_{t+1} = \hat{B}_t + r\hat{B}_t(1 - \frac{\hat{B}_t}{B_\infty}) - C_t \qquad 3.16$$

$$\widehat{U}_t = q\widehat{B}_t \qquad 3.17$$

where the C_t is observed catch, $\widehat{U}_t$ and $\widehat{B}_t$ are predicted catch per unit effort and biomass at year t.

The sum of squared error between observed and predicted CPUEs is calculated. The way of calculation is based on the assumption of the random error being additive or multiplicative. An additive error structure is appropriate when the variability in CPUE is constant as a function of the independent variable, stock biomass. A multiplicative error structure is appropriate when the variability increases as a function of stock biomass. If the random error is additive, the summed error is calculated as:

$$\sum e_t = \left(U_t - \widehat{U}_t\right)^2 \qquad 3.18$$

If the random error is multiplicative, the summed error is calculated as:

$$\sum e_t' = \left(\ln U_t - \ln \widehat{U}_t\right)^2 \qquad 3.19$$

where U_t and $\hat{U}_t$ are observed and predicted catch per unit effort respectively. The parameter values are then adjusted until the summed error $\sum e_t$ or $\sum e_t'$ is minimized. The output of the procedure has the final estimates of q, r, and B_∞.

To start the prediction, the stock size at the beginning of the data series available has to be known. If not, this initial stock biomass (B_1) is usually assumed as:

$$B_1 = \frac{C_1}{qE_1} \qquad 3.20$$

where C_1 and E_1 are the catch and fishing effort at the beginning of the data series. This indicates that there is an important reason to estimate biomass at the beginning of a new fishery.

This time-series fitting method was first proposed and used by Pella and Tomlinson (1969) and regarded by Hilborn and Walters (1992) as the best method for estimating production models. Monte Carlo simulations showed that the observation-error method is the least biased and the most precise, while the equilibrium method is highly biased and the process-error approach is often imprecise (Polacheck et. al. 1993).

4. Production modelling using mortality information

To fit a production model, fishing effort data should be expressed in standardized units to account for differences in size and type of vessels and fishing gears being used and improvement in fishermen's fishing experience. Quinn and Deriso (1999) described several ways of CPUE standardisation. However, these changes are difficult to detect in time to be incorporated into an assessment particularly for developing fisheries. A lack of proper fishing effort calibration can lead to misleading results, particularly when a fishery is in the earlier years when the learning curve of the fishermen is particularly steep (Brown et. al. 1976).

Csirke and Caddy (1983) proposed a new approach that allows fitting of surplus production models using total mortality rate instead of fishing effort (Table 1). This method relies on the same assumptions as the production model and shares most of the limitations of such a simplistic relationship. However, this method avoids the problem of having to correct for changes in fishing power, increases in efficiency and fishing experience, etc. As a bonus, natural and hence fishing mortality rate, can also be estimated. So far, the model can only be fitted by the equilibrium method.

Based on the Schaefer production model and equilibrium assumption, Csirke and Caddy (1983), and Caddy and Defeo (1996) derived the following equation:

$$\frac{Y_i}{Z_i - M} = B_\infty - \frac{B_\infty}{r}(Z_i - M) \qquad 4.1$$

where Y_i is the yield corresponding to year i, M is the natural mortality rate, assumed to be constant and needs to be estimated, Z_i is the total mortality rate for fully available age groups corresponding to year i, B_∞ is the unfished stock biomass and r is the intrinsic rate of population growth. This model conforms to a simple linear model with $Z_i - M$ as the independent variable and $\frac{Y_i}{Z_i - M}$ as the dependent variable.

This simple linear model, however, can not be fitted in a direct way, as M is an unknown parameter, which needs to be estimated. The model has to be fitted by using different trial values of M, calculating the corresponding coefficient of determination, r^2, of the linear model for each trial value of M. The value of M, which results in the largest r^2, will be the estimate of the natural mortality rate and be used to estimate the model parameters, B_∞ and *r*. The primary parameters are calculated as follows:

$$F_{msy} = \frac{r}{2} \qquad 4.2$$

$$Z_{msy} = F_{msy} + M \qquad 4.3$$

$$MSY = \frac{B_\infty}{2} F_{msy} \qquad 4.4$$

where F_{msy} and Z_{msy} are fishing and total mortality rates respectively corresponding to the *MSY*.

When *M* can be independently estimated from field data, it could be used in equation 4.1 to directly estimate the model parameters or to verify the model estimate of *M*.

5. Maximum biological production estimation

The usual concept underlying production models, as noted by Pauly (1979), is that the surplus production is effectively zero for the unfished stock. This, in a sense, ignores the fact that for many stocks, predation is harvesting a significant proportion of prey biomass even in the absence of fishing. In practice, whatever the source of the mortality, the ultimate effect is to remove fish from the stock, although fishing mortality can be controlled by the society (Caddy and Csirke 1983). Caddy and Csirke (1983) and Csirke and Caddy (1983) put forward an interesting idea concerning stock production. When the stock production is considered in response to the total mortality instead of, as in common thinking, the fishing mortality, the biomass production is regarded as biological production. Thus at equilibrium biological production corresponds to the total production being harvested as well as being removed by natural mortality. Caddy and Csirke (1983) postulated that at equilibrium there must be a total mortality level, Z_{mbp}, at which the maximal biological production, MBP, is obtained from the stock.

Based on the Schaeffer model at equilibrium, Caddy and Csirke (1983) showed that Z_{mbp} and F_{mbp} are positively correlated with the intrinsic rate of population growth, r:

$$Z_{mbp} = 0.5(r + M) \qquad 5.1$$

$$F_{mbp} = 0.5(r - M) \qquad 5.2$$

and the maximum biological production (*MBP*) and the biomass to produce MBP (B_{mbp}) and yield corresponding to MBP (Y_{mbp}) are calculated as:

$$MBP = \frac{B_\infty}{4r}(r + M)^2 \qquad 5.3$$

$$B_{mbp} = \frac{B_\infty}{2}(1+\frac{M}{r}) \qquad 5.4$$

$$Y_{MBP} = \frac{rB_\infty}{4}\left[1-\left(\frac{M}{r}\right)^2\right] \qquad 5.5$$

Various simulations showed that F_{MBP} is consistently lower than F_{MSY} and is a conservative reference point (Fig. 1). Die and Caddy (1997) indicated that F_{MBP} can be used as a TRP for a developing fishery.

6. Production model with area information

One of the main implicit assumptions made in using production models is that the data reflect changes in the population size of a single biological unit. However, this assumption is unlikely to be fulfilled in many situations. Many fisheries develop by initially exploiting areas with higher fish densities and then move to less productive grounds. Thus, the same amount of fishing effort does not generate the same fishing mortality or same amount of catch, when effort is exerted in areas with different biomass densities. To account for trends in the areal extent of the fishery, as well as for trends in effort, Die et. al. (1990) developed a production model which incorporates areas of fishing grounds in addition to the catch and fishing effort data.

Suppose there is an unit stock that is only partially exploited. Assume there is no biomass transfer between the exploited and unexploited areas, but the rates of population growth are identical for the two segments of the stock. Based on the logistic growth model the production in the two areas can be described as follows:

$$\frac{dB_1}{dt} = rB_1\frac{kB_\infty - B_1}{kB_\infty} - F_1B_1 \qquad 6.1$$

$$\frac{dB_2}{dt} = rB_2\frac{(1-k)B_\infty - B_2}{(1-k)B_\infty} \qquad 6.2$$

where, k denotes the fraction of the virgin population biomass that is potentially affected by fishing, B_1 is the exploited fraction of the stock and B_2 the unexploited fraction, B_∞ is the unfished population biomass, and F_1 is the fishing mortality rate. When $k = 1$, the entire population biomass is affected by fishing, and the model reduces to the Schaefer model.

At equilibrium, equation 6.1 results in the following relationship:

$$B_1 = kB_\infty - \frac{F_1kB_\infty}{r} \qquad 6.3$$

Multiplying both sides by F_1 results in the following yield equation:

$$Y = F_1 k B_\infty - \frac{F_1^{\,2} k B_\infty}{r} \qquad 6.4$$

where Y is the yield.

Let s be the surface area affected by the fishery and S be the surface area occupied by the whole population (s <= S). We may model k to be a simple power function of the ratio s/S:

$$k = \left(\frac{s}{S}\right)^c \qquad (c>=0) \qquad 6.5$$

where c is a constant. A value of c equal to 1.0 would mean that an increase in s would lead to a proportional increase in k. A value of c less than 1.0 would imply that an increase in s would result in a smaller increase in k. The opposite would be true if c is more than 1.0.

Within the fishing area, s, average catch per unit of effort, U, can be modelled as:

$$U = \frac{Y}{E} = q'ad \qquad 6.6$$

where E is the fishing effort, q' is the catch efficiency (probability of capturing a fish that is in the path of the fishing gear), a is the area fished by one unit of effort, and d is the average density of fish in the area affected by the fishery, which can be expressed as:

$$d = \frac{B_1}{s} \qquad 6.7$$

Yield can be calculated as

$$Y = B_1 F_1 \qquad 6.8$$

Insert equations 6.7 and 6.8 into equation 6.6 and rearrange:

$$F_1 = \frac{q'aE}{s} \qquad 6.9$$

Insert equations 6.5 and 6.9 into equation 6.4:

$$Y = \frac{q'aB_\infty}{S^c} s^{c-1} E - \frac{(q'a)^2 B_\infty}{S^c r} s^{c-2} E^2 \qquad 6.10$$

The linear parameters in the above equation can be combined for simplicity:

$$Y = as^{c-1}E - bs^{c-2}E^2 \qquad 6.11$$

where $a = \frac{q'aB_\infty}{S^c}$ and $b = \frac{(q'a)^2 B_\infty}{S^c r}$. Dividing both sides of equation 6.11 by fishing effort, we get:

$$U = as^{c-1} - bs^{c-2}E \qquad 6.12$$

The parameters, a, b and c can be estimated using a non-linear regression fitting method by treating U as the dependent variable, and E and s as the independent variables.

E_{msy} and MSY are calculated by the following two equations:

$$E_{msy} = \frac{sa}{2b} \qquad 6.13$$

and $$MSY = \frac{s^c a}{4b} \qquad 6.14$$

Both E_{msy} and MSY are the terms relative to the fraction of the population affected by the fishery and increase with increasing s, giving a seemingly good explanation of how the equilibrium relationship has changed with the expansion of the fishery.

Die et. al. (1990) showed that a significantly improved fit was obtained with this method when compared with the Schaeffer model, when data from the fishery for yellow fin tuna in the eastern Pacific are used to illustrate the model's applicability.

7. Yield per recruit modelling

Yield per recruit models examine the trade-off between capturing a large number of fish at low average weight early in their life span and a smaller number of fish at higher average weight later in their life span. Calculation of yield from a given recruitment is important in many stocks, when stock and recruitment relationship is unknown or recruitment is highly variable. Because variation in recruitment is ignored, yield is expressed as the accumulated amount of yield produced by a given fishing mortality for one recruited fish in its whole life span. To calculate yield per recruit, information on growth, natural and fishing mortality rate has to be known (Table 1). There are basically two methodologies for calculating catch per unit effort: the analytical method and the projection method.

7.1. Analytical method

When the growth of fish can be modelled by the von Bertalanffy equation, fish enter the fishery once they reach a certain age, and the recruited population suffers from the same natural and fishing mortality rate, the yield per recruit can be calculated using the following equation derived by Beverton and Holt (1957):

$$Y/R = Fe^{-M(t_c - t_r)} W_\infty \left[\frac{1-e^{-Zl}}{Z} - \frac{3e^{-Kr}(1-e^{-(Z+K)l})}{Z+K} + \frac{3e^{-2Kr}(1-e^{-(Z+2K)l})}{Z+2K} - \frac{e^{-3Kr}(1-e^{-(Z+3K)l})}{Z+3K} \right]$$

…7.1

where F is the fishing mortality rate, M is the natural mortality rate, Z is the total mortality rate (= F+M), t_c is the age at first capture and t_r is the age of recruitment, t_∞ is the maximum age, t_0 is the theoretical age at which fish has zero length, $l = t_\infty - t_r$, $r = t_c - t_0$, W_∞ is asymptotic weight, and K is the von Bertalanffy growth coefficient.

Ricker (1975) stated that this equation is more complex than is necessary for many purposes. When t_∞ is large, he simplified the above equation as:

$$Y/R = Fe^{-M(t_c - t_r)} W_\infty \left(\frac{1}{Z} - \frac{3e^{-Kr}}{Z+K} + \frac{3e^{-2Kr}}{Z+2K} - \frac{e^{-3Kr}}{Z+3K} \right) \qquad 7.2$$

To see how yield per recruit varies with rate of fishing and age of first capture, we calculate yield per recruit by varying F and t_c. When M/K is small, it will pay in terms of getting the best yield from a recruited level to fish relatively lightly and with a large size at first capture. If M/K is large, many fish will die before completing much of their growth, and it will therefore pay to fish relatively hard and with small size at first capture (Gulland 1983).

Given a fixed age of first capture, yield-per-recruit can be graphed as a function of fishing mortality (Fig. 2). The fishing mortality corresponding to the maximum yield-per-recruit is the F_{max}. In short-lived species with high mortality rates, the results of yield per recruit analyses may be quite misleading, often suggesting that an extremely high, or sometimes infinite fishing mortality is required to secure the maximum yield. F_{max} was traditionally often used as an TRP, but nowadays, tends to be regarded as an LRP (Caddy 1998). The TRP is often set to be $F_{0.1}$, a fishing mortality rate where the slope of the yield per recruit function is 0.1 times the initial slope (Fig. 2). $F_{0.1}$ will always be less than F_{max}. Probably the most important aspect of $F_{0.1}$ strategies is that they are totally ad hoc, but often appear to be in the right ball park (Hilborn and Walters 1992).

7.2. Projection method

The method first calculates the amount of catch and biomass at each age from a given recruit and then summarise the catch and biomass.

Given an (assumed) number recruit (R), the number of fish reaching the age vulnerable to the fishing gear (N_c) will be:

$$N_c = \mathrm{R}e^{-M(t_c - t_r)} \qquad 7.3$$

where t_c is the age at first capture and t_r is the age of recruitment. The number of fish at the beginning of age a+1 (N_{a+1}) is related to the number of fish living at the beginning of age a (N_a):

$$N_{a+1} = N_a e^{-Z_a} \qquad 7.4$$

where Z_a is the total mortality rate for fish at age a. The catch of fish in weight at age a (C_a) from this recruitment is calculated as:

$$C_a = \overline{W}_a F_a \overline{N}_a \qquad 7.5$$

where $\overline{W}_a$ is the average weight of fish at mid-point of age a, $\overline{N}_a$ is the average number of fish at age a. F_a is the age-specific fishing mortality rate for the fish at age a and may be calculated as:

$$F_a = S_a F \qquad 7.6$$

where S_a is the relative gear selectivity and F is the fishing mortality on the age of fish considered to be fully vulnerable. The average number of fish at age a is related to the number of fish at the beginning of age a:

$$\overline{N}_a = \frac{N_a}{Z_a}(1 - e^{-Z_a}) \qquad 7.7$$

The total catch in weight, i,e, the yield (Y), is:

$$Y = \sum_{a=t_c}^{t_\infty} C_a \qquad 7.8$$

where t_c is the age at first capture and t_∞ is the symptotic age of the fish. The biomass for age a (B_a) is:

$$B_a = \overline{W}_a \overline{N}_a \qquad 7.9$$

The total catchable biomass (B_{tot}) is:

$$B_{tot} = \sum_{a=t_c}^{t_\infty} B_a \qquad 7.10$$

The spawning stock biomass (SSB) is:

$$SSB = \sum_{a=t_m}^{t_\infty} P_a B_a \qquad 7.11$$

where t_m is the age at maturity, P_a is the proportion of the age group reaches maturity. Yield-per-recruit, Biomass-per-recruit and Spawning Stock Biomass per Recruit are simply calculated by dividing yield, total biomass spawning stock biomass by the recruits respectively.

Information required to use the projection method is the same as for the analytic yield per recruit analysis, namely growth, mortality and age at first capture. However, this method is far more flexible than the classical Beverton and Holt method. Any type of growth information, such as length and weight at age, can be easily incorporated. Fishing mortality rates do not have to be the same across all ages. Moreover, this process can be easily generalized to allow inclusion of stock-recruitment information and complex exploitation patterns.

8. Combination of spawning stock biomass per recruit and stock-recruitment analysis

Unlike yield per recruit, SSB per recruit is at a maximum when fishing mortality rate is zero and decreases monotonically as fishing mortality increases. Fishing mortality combined with age at first capture reduces the amount of SSB per recruit, which can be expressed as a percentage of the maximum SSB per recruit (when F = 0). The corresponding fishing mortality is noted as $F_{\%SPR}$. For instance, the fishing mortality results in a 30% reduction in SPR is $F_{30\%SPR}$. When no information on stock and recruitment relationship is available, $F_{\%SPR}$ may be used as TRPs or LRPs depending on the percentage.

Recently, reference points based on SSB per recruit have been defined based on the relationship between SPR and the survival ration (Recruit/SSB) obtained from pairs of stock recruitment observations (Table 1). This enable people to determine what amount (percentage) of SSB per recruit should be preserved based on the degree of resilience of the stock, and thus offers an objective way of setting up reference points. The concept of F_{low}, F_{med}, and F_{high} introduced by Anon (1984, 1985) represents a family of biological reference points based on the combined analysis of SSB per recruit and recruitment versus SSB scatter diagram (Fig. 3). The procedure for estimating these three parameters is as follows:

(1) make a scatter plot of recruitment versus SSB

(2) draw lines through the origin which leave 90% (F_{low}), 50% (F_{med}) and 10% (F_{high}) of the points above the line. Thus the slopes correspond to values of recruits per unit SSB and the reciprocals are SSB/recruit

(3) make a graph of SSB per recruit on fishing mortality. SSB per recruit is at a maximum when fishing mortality is zero and decreases monotonically as fishing mortality increases

(4) from the graph, locate points of SSB per recruit which equal the reciprocals of the lines for F_{low}, F_{med} and F_{high}

(5) the corresponding fishing moralities are read off from the x-axis.

F_{med} corresponds to the level of fishing mortality where recruitment has been sufficient to balance the mortality about 5 years out of 10. With fishing at the F_{med} level, there is, therefore, a good chance that the stock will be sustained.

F_{low} represents a level of fishing mortality where recruitment has been sufficient to balance the mortality about 9 years out of 10. The likelihood of a decline in the stock at this level of exploitation is therefore low and increase is more likely.

F_{high}, on the other hand, represents a level of fishing mortality where recruitment has been insufficient to balance the mortality in about 9 times out of 10. The likelihood of a decline in the stock at this level of exploitation is therefore high.

Data required for estimating these parameters are the same as for F_{max} or $F_{0.1}$ except for a scatter plot of recruitment versus SSB and a proportion of maturity at each age. Use of reciprocal of the slope of a line implies that only the survival ratio (Recruit/SSB) obtained from pairs of stock recruitment observations are used in practice. Therefore, the scatter plot does not have to have the actual recruits and SSB data. Recruitment index and SSB index data can be used instead, as long as the ratio of the recruitment index to actual recruits is same as the ratio of SSB index to actual SSB. For instance, assume we have a fishery on an exploited stock, where the fish recruit to the fishery at age 3 and reach maturity at age 4. Suppose we have 10 years of catch per unit effort data for age 3 ($CPUE_{3,\,i}$) and above ($CPUE_{3+,\,i}$) (*i* indicates the year (1, 2, …10)). We also know the average weight of the fish at age 3 is $\overline{W}_3$. Assume that the CPUE is proportional to the biomass:

$$B_{3,i} = qCPUE_{3,i} \qquad 8.1$$

$$SSB_i = qCPUE_{3+,i} \qquad 8.2$$

where $B_{3,i}$ and SSB_i are the biomass at age 3, and age 4 and above (the spawning stock biomass) in year i respectively, q is the catchability coefficient.

When recruitment is expressed as pieces, we need to calculate the recruit in year i (R_i):

$$R_i = \frac{qCPUE_{3,i}}{\overline{W}_3} \qquad 8.3$$

To make a scatter plot, we could just plot $\frac{CPUE_{3,i+3}}{\overline{W}_3}$ against $CPUE_{3+,\,I}$, instead of plotting R_{i+3} against SSB_i.

In many studies recruitment is notoriously variable and it is difficult to obtain a statistically significant fit to a traditional stock-recruitment relationship, such as those of Ricker (1954) and Beverton and Holt (1957) (Maguire and Mace 1993). This method offers an alternative approach, by considering the probability of obtaining strong, average or poor recruitment at various spawning biomass levels, to incorporate the information on stock and recruitment into stock dynamic analyses.

Yield per recruit analysis can be used to assess the possibility of growth overfishing. As it ignores the variability in recruitment, the effect of exploitation on recruitment overfishing is ignored. Incorporation of recruitment and stock relationships into the yield and SSB per recruit analysis enable us to assess the impact of fishing patterns not only on the growth overfishing but also on recruitment overfishing.

9. Assumptions for the assessment models

All the models described in this paper assume that the exploited population behaves in a more or less regular fashion and past series of fisheries data can be used to make assertions as to the likely future behaviour of the system. They also assume that fisheries operate on the unit stock defined as a closed, self-sustaining unit of population, and all losses from the population are due to natural and fishing mortality (no immigration or emigration). They further assume that fishing mortality is proportional to the effort and all fish are available to the fishery and equally vulnerable to gear except for the production model utilizing areal data.

9.1. Biomass Production Model

The catch and effort data reflect changes in the population size of a single biological unit. The catchability coefficient is a constant. The rate of biomass production is a function of biomass only, and has nothing to do with the population age-structure.

9.2. Production model using total mortality instead of fish effort.

Catch is equal to surplus production, i.e. equilibrium catch. Other assumptions are the same as for the production model.

9.3. Maximum Biological Production model

Biological production is a function of biomass only, and has nothing to do with the population age-structure. Biological production equals to the catch and what removed by natural mortalities (i.e. equilibrium assumption). Other assumptions are the same as for the production model.

9.4. Yield-per-recruit and Biomass-per-recruit model

Fishing patterns or environmental factors have no effect on recruitment, which is assumed to be constant. Natural mortality rate is invariant with age, time, or locations.

The average size of an age is invariable. Fish of same age have the same catchability.

9.5. F_{med}, F_{low} and F_{high} estimation

The historic range of variation in the ratio of spawning stock biomass to recruit persists into the future. There is no compensatory or depensatory effect on stock and recruitment relationship. Other assumptions are the same as for yield-per-recruit model.

10. Simulations and Bayesian Analysis

Most people now accept errors in variables as an intrinsic problem in estimation for fisheries, and rather than trying to correct the estimates, they try to understand how large the bias is likely to be (Hilborn and Walters 1992). Simulations are often used to assess the relative levels of confidence on the parameter estimates. Among the most commonly used simulation techniques are Bootstrapping and Monte Carlo methods.

10.1. Bootstrapping

Bootstrap was developed by Efron (1979, 1981, 1982, 1987) and proved to be very useful in assessing the variance in parameter estimates.

When a set of n data can be considered to be independent and from the same probability distribution, we could generate many (a few hundred) sets of n data by randomly resampling with replacement the original set of the data. After we use the original data to fit a model and estimate parameters, we could use each one of the regenerated data sets to fit the same model and estimate the same parameters. In this way, we have a few hundred estimates of the same parameters, which allows us to examine probability distributions for the parameters.

The above technique is easy to use and effective. However, most fisheries data are of time-series nature and are, therefore, often not truly independent. Nonparametric bootstrap may have to be used instead.

Suppose we have a time series of $CPUE_i$ and $Catch_i$ data for n years of observations (i = 1, 2…n). We use the observation-error method (equations 3.16 and 3.17) to fit the biomass production model, estimate a primary parameter, such as MSY, as $CPUE_i'$, and obtain our best predictions of $\widehat{CPUE}_i$. The residuals (r_i) from the model fit are:

$$r_i = CPUE_i - \widehat{CPUE}_i \qquad 10.1$$

Assume the residuals are a sample of the error representing the random component in the input data, and the error is additive. Further, assume all the errors are from the same probability distribution. We can then generate a new data set by randomly sampling from the residuals, with replacement, n residual samples (r_j, j = 1, 2…n), and adding one residual to each predicted data point to get a new data series ($CPUE_i'$) similar to but different from the initial one:

$$CPUE_i' = \widehat{CPUE}_i + r_j \qquad 10.2$$

We then use the $CPUE_i'$ values to fit the model again, and obtain new parameter estimates for the model. We repeat this process a few hundred times. We then have a few hundred estimates of the parameters and MSY, which enable us to examine the parameter variances and covariances, and bias in MSY estimation. The bias is estimated as the difference between the mean of the bootstrap estimates and the original estimate, $M\hat{S}Y$.

To construct a confidence interval for MSY, we may take the standard deviation of the bootstrap estimates of MSY and calculate the confidence interval by assuming it is the true standard deviation. Alternatively and preferably, we can establish a confidence interval from the frequency distribution of the bootstrap estimates of MSY, especially when the frequency distribution appears very asymmetry. For instance, if we want to construct a 90% (so $\alpha = 0.05$) confidence interval for MSY, we need to calculate a lower bound and upper bound of the interval. We set the lower bound of the interval to be a value so that the cumulative probability of bootstrap estimates smaller than this value will equal to α, and the upper bound to be a value so that the cumulative probability of bootstrap estimates smaller than this value will equal to $1-\alpha$.

If the error is assumed to be multiplicative instead of additive, the residuals are calculated using the following equation:

$$r_i = \ln CPUE_i - \ln C\overset{\cap}{P}UE_i \qquad 10.3$$

and a new data series should be generated as follows:

$$\ln CPUE_i' = \ln C\overset{\cap}{P}UE_i + r_j \qquad \text{or}$$

$$CPUE_i' = C\overset{\cap}{P}UE_i \, e^{r_j} \qquad 10.4$$

10.2. Monte Carlo simulation

The Monte Carlo method came into being in 1949, when an article entitled “The Monte Carlo Methods” was published by two American mathematicians, Metropolis and Ulam (1949).

The Monte Carlo method is a method of approximately solving mathematical problems by the simulation of random quantities. The computational algorithm consists, in general, of a process for producing a random event. The process is repeated many times, each trial being independent of the rest, and the results of all the trials are averaged together. The Monte Carlo method makes possible the simulation of any process influenced by random factors, once the probability distribution can be derived.

Let us use the same time series of data of $CPUE_i$ and $Catch_i$, as described above, as an example. We use the data to fit the biomass production model by Walters and Hilborn’s non-equilibrium method with an additive error:

$$CPUE_{i+1} = CPUE_i + rCPUE_i(1 - \frac{CPUE_i}{B_\infty q}) - qCatch_i + ei \qquad 10.5$$

where ei is a normally distributed random variable with a mean of 0.0 and a standard deviation of s. By the maximum likelihood method, we find the best estimates of the parameters, $\widehat{B}_\infty$, $\widehat{q}$ and $\widehat{r}$, and the best estimate of the standard deviation, $\widehat{s}$. The primary parameters, MSY and E_{msy}, can be calculated based on the values of $\widehat{B}_\infty$, $\widehat{q}$ and $\widehat{r}$ (see equation 3.14 and 3.15). The current state of the art is to do simulations assuming the estimates of the parameters are correct. We simply generate a time series of CPUE data by using the estimates of the parameters, $\widehat{B}_\infty$, $\widehat{q}$ and $\widehat{r}$, and observed $CPUE_i$ and $Catch_i$ in equation 10.5 plus a random error generated from the estimated normal distribution with mean = 0 and sd = $\widehat{s}$. We then use the simulated data to fit the model 10.5 and obtain the estimates of the primary parameters, MSY and E_{msy}, again. After we repeat this process for a few hundred times, we can then examine the variance and covariance of these parameters.

10.3. Bayesian Analysis

Bayesian statistics was developed more than two hundred years ago by the Reverend Thomas Bayes (1763). It has now been increasingly applied in fisheries stock assessment to evaluate the probability distribution for uncertain parameters.

Bayesian statistics differs fundamentally from the classic statistics in the definition of probability. Classical statistics defines probability as the expected frequency of occurrence of events under random sampling from a well-defined sample space. Parameters are viewed as, although unknown, fixed values. So in classical statistics context a parameter value does not have a probability distribution. Bayesian statistics defines probability as a measure of credibility. Thus it makes perfect sense to talk about the probability of a parameter value in a Bayesian statistics context. Another distinctive feature of Bayesian statistics is to incorporate pre-beliefs (prior probabilities) about alternative parameter values into the analysis.

The objective of Bayesian analysis is to calculate the probability distribution associated with each unknown parameter in a model based on the Bayes theorem:

$$p(x \mid d) \propto L(x \mid d) \times p(x) \qquad 10.6$$

where $p(x \mid d)$ is the probability of a parameter value given the data, *d*, which is known as the posterior probability; $L(x \mid d)$ is the likelihood of the data given a particular parameter value, x; $p(x)$ is the pre-believed probabilities of alternative parameter values, which is known as the prior probability. The Bayes theorem simply says that "posterior is proportional to likelihood times prior" (see Lee 1989, Carlin and Louis 1998 for more detail). The constant of proportionality (*c*) can be calculated as follows:

$$c = \frac{1}{\sum L(x \mid d) \times p(x)} \qquad 10.7$$

in the discrete case, or

$$c = \frac{1}{\int L(x \mid d) \times p(x) dx} \qquad 10.8$$

in the continuous case. The denominator is just the sum of probabilities over all possible parameter values. The likelihood of the data, $L(x \mid d)$, is formulated by first formulating the probability of observing the data, $p(d \mid x)$, given a parameter value, and then multiplying by a constant, *k*:

$$L(x \mid d) = k \times p(d \mid x) \qquad 10.9$$

For fisheries stock assessment, we are often interested in the probability distribution for parameters, which are of important concerns for management, such as MSY and the unfished stock biomass. Again let us use the time series of $CPUE_i$ and $Catch_i$, as described for Bootstrapping and Monte Carlo simulation, as an example. Assume that each observation of $CPUE_i$ is a random variable sampled from a normal distribution with mean U_i and variance j (i = 1, 2…n). For simplicity, we also assume that the variance, φ, is the same for all observed $CPUE_i$. The variance may be set to a reasonably "guessed" value or be calculated in the following manner:

$$j = \frac{\sum_{i=1}^{n} \left(CPUE_i - U_i\right)^2}{n} \qquad 10.10$$

The probability of observing $CPUE_i$, $p(CPUE_i|U_i)$, is:

$$p(CPUE_i \mid U_i) = \frac{1}{\sqrt{2pj}} e^{-\frac{(CPUE_i - U_i)^2}{2j}} \qquad \text{(i = 1, 2…n)} \qquad 10.11$$

So the likelihood, $L(U_i|CPUE_i)$, is:

$$L(U_i \mid CPUE_i) = k \times \frac{1}{\sqrt{2pj}} e^{-\frac{(CPUE_i - U_i)^2}{2j}} \qquad \text{(i = 1, 2…n)} \qquad 10.12$$

where k is any constant. If we choose k to be $\sqrt{2pj}$, equation 10.12 becomes:

$$L(U_i \mid CPUE_i) = e^{-\frac{(CPUE_i - U_i)^2}{2j}} \qquad \text{(i = 1, 2…n)} \qquad 10.13$$

Suppose we have a prior belief that U_i follows a normal distribution with a mean of U_{0i} and a variance of V_{0i}. So the prior probability, $p(U_i)$, is:

$$p(U_i) = \frac{1}{\sqrt{2pV_{0i}}} e^{-\frac{(U_i - U_{0i})^2}{2V_{0i}}} \qquad \text{(i = 1, 2…n)} \qquad 10.14$$

The posterior probability for U_i, $p(U_i \mid CPUE_i)$, is formulated as follows:

$$p(U_i \mid CPUE_i) \propto L(U_i \mid CPUE_i) \times p(U_i) = \frac{1}{\sqrt{2pV_{0i}}} e^{-\frac{(CPUE_i - U_i)^2}{2j} - \frac{(U_i - U_{0i})^2}{2V_i}} \qquad 10.15$$

Because V_{0i} is a constant, the equation 10.15 can be simplified as:

$$p(U_i \mid CPUE_i) \propto e^{-\frac{(CPUE_i - U_i)^2}{2j} - \frac{(U_i - U_{0i})^2}{2V_i}} \qquad (i = 1, 2 \ldots n) \qquad 10.16$$

The posterior probability (*p*) of observing *CPUE*$_1$, *CPUE*$_2$…**and** *CPUE*$_n$ is just the product of every single posterior probability:

$$p = \prod_{i=1}^{n} p(U_i \mid CPUE_i) \propto \exp\left(-\sum_{i=1}^{n} \frac{(CPUE_i - U_i)^2}{2j} - \sum_{i=1}^{n} \frac{(U_i - U_{0i})^2}{2V_{0i}} \right) \qquad 10.17$$

The constant of proportionality (c) is the inverse of the summation of probabilities over all possible values of these parameters:

$$c = \frac{1}{\int \underset{n}{\cdots} \int \exp\left(-\sum_{i=1}^{n} \frac{(CPUE_i - U_i)^2}{2j} - \sum_{i=1}^{n} \frac{(U_i - U_{0i})^2}{2V_{0i}} \right)} \qquad 10.18$$

When we do not have any idea about prior probability of parameter values, we could simply use an uniform prior by assigning the same prior probability for all possible parameter values. In our example, we could simply assume the variances of the prior probability distributions are very, very large. Mathematically, we may write:

$$V_{0i} = \infty \qquad (i = 1, 2 \ldots n) \qquad 10.19$$

When uniform priors are adopted, the posterior probability of observing *CPUE*$_1$, *CPUE*$_2$…**and** *CPUE*$_n$ becomes:

$$p \propto \left(-\frac{\sum_{i=1}^{n} CPUE_i - U_i)^2}{2j} \right) \qquad 10.20$$

The constant of proportionality (*c*) is:

$$c = \frac{1}{\int \underset{n}{\cdots} \int \exp\left(-\frac{\sum_{i=1}^{n} (CPUE_i - U_i)^2}{2j} \right)} \qquad 10.21$$

To calculate the posterior probabilities, we need to know the value of U_i, which can be estimated through the biomass production modelling:

$$\hat{B}_{i+1} = \hat{B}_i + r\hat{B}_i(1 - \frac{\hat{B}_i}{B_\infty}) - C_i \qquad 10.22$$

$$\hat{U}_i = q\hat{B}_i \qquad 10.23$$

where the C_i is observed catch, $\hat{B}_i$ and $\hat{U}_i$ are predicted biomass and catch per unit effort (estimate of U_i) at year *i* respectively, and *r*, *q*, and B_∞ are the parameters of the production model.

For most fisheries assessments, the Bayes posterior probability is calculated by means of a non-linear estimation of the likelihood at many different trial parameter values. We may set up a grid of parameter values over which we are to calculate the posterior probability at each grid point. To reduce the number of parameters involved in grid computation, we might treat the less important parameter, such as *q*, as a "nuisance" parameter, which is to be represented only by a maximum likelihood estimate. In our example, the likelihood (*L*) of q can be formulated as follows:

$$L = \exp\left(\frac{-\sum_{i=1}^{n}\left(CPUE_i - q\hat{B}_i\right)^2}{2j} \right) \qquad 10.24$$

The log likelihood (*l*) is:

$$l = \ln(L) = \left(\frac{-\sum_{i=1}^{n}\left(CPUE_i - q\hat{B}_i\right)^2}{2j} \right) \qquad 10.25$$

Taking the derivative of the log likelihood function with respect to the parameter, *q*, then setting the derivative equal to zero, and solving for *q*, we obtain the maximum likelihood estimate of *q* as:

$$q = \frac{\sum_{i=1}^{n} CPUE_i \times \hat{B}_i}{\sum_{i=1}^{n} \hat{B}_i^{\,2}} \qquad 10.26$$

Now we are ready to set a range and an increment for each of the more important parameters, *k* and *B*¥. The range should be large enough to cover all the plausible values for the parameter, and the increment, which determines the number of grids within the range, should be reasonably fine. Suppose we define a range for *r* to be 0.1-0.5 with an increment of 0.01, and a range for B_∞ to be 1,000-5,000 with an increment of 100. So there are 50 grids for each parameter and 50^2 = 2500 different grid combinations. At each combination, we simulate the model forward in time over the period for which we have data, calculating predicted values for the U_i and do the probability calculation. A computer program is needed to complete this tedious task. The calculation procedure can be summarized as follows:

(1) let r = 0.1 and B_∞ = 1,000;

(2) iteratively use equation 10.22 to calculate $\hat{B}_i$ (assume $\hat{B}_1 = B_\infty$), and also compute $\sum_{i=1}^{n} \hat{B}_i^{\,2}$ and $\sum_{i=1}^{n} CPUE_i \hat{B}_i^{\,2}$ (i = 1, 2…n) along the way for calculation of q;

(3) use equation 10.26 to calculate the maximum likelihood estimate of q;

(4) use equation 10.23 to calculate $\hat{U}_i$ (i = 1, 2…n);

(5) use equation 10.10 to calculate the variance, j;

(6) calculate likelihood times prior probability (*LP*) for this value of r and B_∞ (refer to equation 10.17 or 10.20):

$$LP = \exp\left(-\sum_{i=1}^{n} \frac{(CPUE_i - U_i)^2}{2j} - \sum_{i=1}^{n} \frac{(U_i - U_{0i})^2}{2V_{0i}} \right) \text{ or}$$

$$LP = \exp\left(-\sum_{i=1}^{n} \frac{(CPUE_i - U_i)^2}{2j} \right) \text{ (if uniform prior is adopted);}$$

(7) Add this value of *LP* onto a variable, *SP*, which stores the total probability over all the combination of grid values; SP is equivalent to the denominator of equation 10.18 or 10.21, but calculated in a discrete manner instead;

(8) Take one proper sup-step out of the three: <1> increment B_∞ by 100 and let r remain the same value, if $B_\infty \neq 5{,}000$; do the calculation again from step 2 to 7; <2> increment r by 0.01 and set B_∞ to 1,000, if B_∞ = 5,000 and $r \neq 0.5$, do the calculation again from step 2 to 7; <3> go to step 9, if r = 0.5 and B_∞ =5,000 (i.e. every grid combination has been evaluated);

(9) Calculate the posterior probability, $P(r,\ B_\infty)$, for each grid combination:

$P(r, B_\infty) = \frac{LP}{SP}$, ($r$ = 0.1, 0.11, 0.12…0.5; B_∞ = 1,000, 1,100, 1,200…5,000).

The posterior probability matrix derived from the above calculation can be used to estimate posterior probabilities for primary parameters, which are derived from the production model parameters. For instance, we want to know the posterior probability distribution for MSY, which is predicted from the production biomass model. We can set up a series of MSY "bins", each representing a narrow range of MSY values, and set up an array to store the probability for each bin. For combination of each value of r and

B_∞, estimate MSY ($MSY = \frac{rB_\infty}{4}$), determine which MSY bin this estimate falls into, and then add the corresponding posterior probability for this combination of r and B_∞, $P(r,\ B_\infty)$, to the total probability for this bin, stored in the array. After the calculation is completed for each value of r and B_∞, the posterior probability distribution for MSY is represented by the probability contained in MSY bins. To have a, say 90%, confidence interval for the MSY, we could find the confidence bounds simply by chopping off 5% at each tail of the posterior probability distribution for MSY.

11. An example of setting LRP and TRP

FAO (1993) suggested that a LRP be a deterministic value that participants agree represents a safe upper limit for exploitation by a fishery when the current rate of exploitation is known with relatively low precision. It is no longer a target for management, but helps define a target RP at a lower exploitation level. Because LRPs are to be avoided, the probability of exceeding the values must, by definition, be very low. This means that TRP for exploitation rate has to be set considerably lower than the LRP. Within ICES, the TRP is set in such a way that the probability of exceeding the LRP will be no greater than 5% in any given year (Serchuk et. al. 1997).

Caddy and McGarvey (1996) suggest that the LRP should be set first. Choosing a LRP before a TRP leaves open how the TRP might be calculated. This TRP may not be independently defined by technical criteria. Rather, it can be set according to the level of management caution and the believed statistical uncertainty in the exploitation rate estimate. When fishing is aimed at the TRP, the LRP will be exceeded only with a low, preagreed-upon probability. Caddy and McGarvey (1996) illustrate the approach with fishing mortality (F). The methodology can be easily extended to other control variables, such as stock biomass.

Suppose agreement is reached on a maximum limit to the desirable rate of fishing and we assume this corresponds to F_{msy}. This value will be taken as established by convention without variance. Uncertainty in the F estimate will be substantial for most fisheries. The estimation error may be assumed to follow normal or log normal distribution.

The “risk” of overshooting the established LRP, even though the best estimate of the fishing mortality (F_{now}) falls below F_{msy}, is quantified as the probability ($P(F>F_{msy})$) corresponding to the right tail of a normal distribution function lying beyond F_{msy} (Fig. 4). The actual current fishing rate may be any value encompassed by the probability distribution surrounding the best current estimate of F_{now}. Therefore, it would be wise to set the TRP sufficiently below the agreed-upon LRP, F_{msy}, so as to allow for an agreed-upon margin of error (for instance 10%). The narrower the margin of acceptable error, the lower the TRP should be set. The greater the standard deviation, the lower managers should set the acceptable risk. Given these assumptions, we seek to find a value for TRP, that lies safely below F_{msy} such that the probability of the actual F being greater than F_{msy}

is small. Caddy and McGarvey (1996) introduced a formula derived by Abramowits and Stegun (1970), for an approximation solution, accurate to three significant digits:

$$F_{now} = \frac{F_{msy}}{1 + CV(t - \frac{2.30753 + 0.27061t}{1 + 0.99229t + 0.04481t^2})} \qquad 11.1$$

where $t = \sqrt{\ln\left\{\frac{1}{\left[P(F > F_{msy})\right]^2}\right\}}$ and CV is the coefficient of variation of the normal distribution (= standard deviation/mean).

The approach does not seem to be heavily distribution specific. The normal distribution may be not ideal for modelling fishing mortality rates, as it has the defect of not excluding negative values of F. the lognormal distribution is, thus, intuitively appealing. However, Caddy and McGarvey (1996) showed that if the acceptable probability of overshoot is not too low (>= 5%) and *CV* of error distribution not too large (*CV* <= 0.5), a choice between the two common probability distributions for uncertainty does not strongly affect the outcome.

12. Discussion

As specified by the FAO code of Conduct for Responsible Fisheries (FAO 1995c) and the UN agreement on Straddling Fish Stock and Highly Migratory Fish Stocks (UN 1995), one operational component of a precautionary management system is to set up a pair of reference points (RPs). The TRP should be set considerably below the LRP as the target for fishery exploitation. LRP must not be assumed in any way that it may itself serves as exploitation rate. LRP should not be approached and definitely not be exceeded.

The reference points (RPs) used in the fisheries management are usually derived either from some empirical analysis or some sorts of modelling depending on quality of biological and fisheries information. This paper intends to help people in identifying proper quantitative or semi-quantitative methods for formulating RPs based on the biological and fisheries information they have on hand. On the other hand, it also tries to help people in determining what kinds of data they should collect for formulating certain RPs in a new or developing fishery. The fitting procedure for each assessment model is reasonably adequate. Although parameters and RPs can be estimated by following these procedures, it is always a good idea to read some other related references and source materials, which deal with the specific assessment methodologies in more detail.

A new or developing marine invertebrate fishery usually lacks adequate information, such as a time series of catch and fishing effort data or growth and natural mortality rate, allowing RPs to be formulated from modelling. In these cases, empirical equations described in section 2 have to be used. Parameter estimates out of these analyses are rough, but allow the fishery to have an early start or progress. They need to be refined later in light of accumulated time series of data collected while the fishery is evolving. It would also be wise to set reference points in a more precautionary fashion. For instance, a high variation is to be assumed in using Caddy's method described in section 11 to set a TRP, which will force the exploitation rate at a low level.

Production modelling is simple and does not require age or stock recruitment data, which are often lacking in marine invertebrate fisheries. The species most suitable for production modelling are those which have low natural mortality rates, low recruitment variability, and high intrinsic rates of increase (Punt 1995). Although some authors have questioned the use of simple production models in assessments (Morgan 1979, Roff 1983), Ludwig and Walters (1985) and Punt (1992) demonstrated that biomass production modelling is not necessarily inferior to the more detailed population modelling, such as age-structured models, and in some cases it outperforms the age-structured models. The method of fitting production models is most important in obtaining reliable estimates of parameters (Hilborn and Walters 1992, Polacheck et al. 1993). They argued that the observation error time series fitting should always be used, as it provides, in most cases, the least biased estimates when compared with the equilibrium method or process-error method. The data requirement is the same for all these three methods. However, the equilibrium method does not inevitably appear to be less precautionary, as the model performance may depend on the number of years used for adjust for departure from equilibrium (Laloe 1995). The most rigorous approach is to fit the production model using all these three methods, then use the Monte Carlo or bootstrapping simulations to assess the bias in parameters estimation, and finally to choose the most precautionary and reliable estimates for RPs. If time or resources do not allow such a rigorous approach, the observation-error method should be used in favour of the other two methods.

One of the major inherent problems of using fishing effort data in production modelling is to deal with the change in catchability coefficient, q, especially during a developing stage of a marine invertebrate fishery, when the fishing experience and techniques improve quickly. To eliminate this problem, a time-series of total mortality rate may be used instead of fishing effort (Caddy and Csirke 1983). Total mortality rate can be estimated by the catch equation, mean length in the catch, length frequency data, etc. An interesting and seemingly precautionary alternative reference point to MSY (F_{msy}) is MBY (F_{mby}), the maximum biological yield, which can also be estimated. Various simulations have shown that F_{mby} is lower than F_{msy} and may be used as a TRP (Die and Caddy 1997).

The dynamic pool assumption of perfect mixing of individual species and random distribution of fishing effort is particularly weak for sedentary and mobile but territorial species. This is especially true at early stages of a fishery, which are characterized by progressive geographical expansion of the fishing grounds. When information on the area of fishing grounds is available in addition to catch and fishing effort, the areal production model developed by Die et al. (1990) (see section 6) may be used to formulate RPs, such as F_{msy}, relative to the fishing area. The model described in section 6 assumes no biomass exchange between exploited and unexploited segments. However, many benthic marine invertebrates are of metapopulation in nature. When biomass exchange at larval stages is substantial, this method may not yield reliable estimates.

For fitting production models with total mortality rate and the areal production model, only the equilibrium method has been developed and there is no long history of application. Therefore, whenever possible, results of these methods should be compared with methods of assessment more commonly in use to ensure that they result in more precautionary and realistic RPs.

Marine invertebrate species are generally difficult to age. However, some species, such as shrimps, do not have a long life span and their ages may be derived from length frequency analysis. When growth or average length at age can be determined, yield per recruit modelling can be employed to search for a fishing pattern with small risk of growth over-fishing. To assess the impact of a fishing pattern on recruitment over-fishing, spawning stock biomass per recruit (SSB per recruit) modelling can be used. The concept of SSB per recruit is analogous to yield per recruit but examines the question of RPs from a different perspective. It answers the question of how much biomass from each recruit should be left rather than should be taken as answered by the yield per recruit modelling. The RP derived from such an analysis is usually $F_{\%spr}$, a fishing mortality rate resulting in a certain percentage of the maximum spawning stock biomass per recruit. When stock and recruitment information are not available, there is no biological basis for selecting one level of %SPR over another. The amount of biomass which should be left in the stock has to be determined based on experience from other similar fisheries or even arbitrarily. Knowledge of stock and recruitment relationships provides a biological and objective way to determine how much biomass should be left to sustain the population. Absolute stock and recruitment data are hard to obtain from the field for a marine invertebrate fishery. They may be generated through virtual population analysis. A more practical way is to estimate index of SSB and recruits, such as CPUE for the age at recruitment and the ages for maturity, as described in the paper.

All these models were initially developed and have been mostly used for finfish fisheries. Advantages and disadvantages of various models are also learned from their application on finfish fisheries. Therefore, as pointed out by Perry et al. (1999), the assumptions of these models must be carefully examined to ensure that they are appropriate for any specific new or developing invertebrate fishery. It is also worth noting here that all of the model-based RPs, and the parameters they are derived from, are only known approximately, often with a poorly defined level of error. In addition, the effect of environmental change on the stock dynamics is ignored. Thus, it is desirable to set LRPs and TRPs precautionarily, especially for a new and developing fishery, where the biological and fisheries information is poor. A RP derived from a modelling or empirical analysis may need to be adjusted (reduced) by a precautionary (maybe arbitrary) fraction to account for uncertainties in parameter estimation, input data and environmental changes.

Recommendations:

(1) Move towards developing reference points in invertebrate stock assessments.
(2) Establish pre-agreed management actions which would be implemented according to the performance of the fishery in relation to the reference points.

(3) Regular review and updating of the reference points in light of new information.

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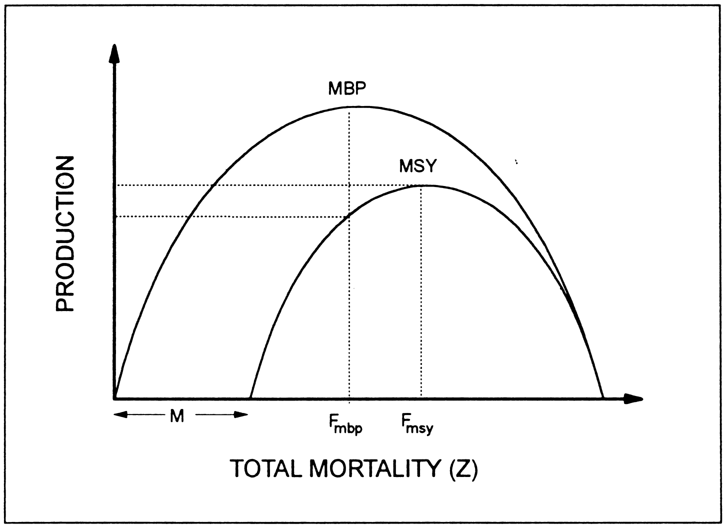

Fig. 1. The equilibrium Schaefer model, showing MSY and MBP (Maximum Biological Production), and corresponding fishing mortality rate, F_{msy} and Fmbp. Note that $F_{mbp} < F_{msy}$. (Excerpt from Caddy and Mahon 1995).

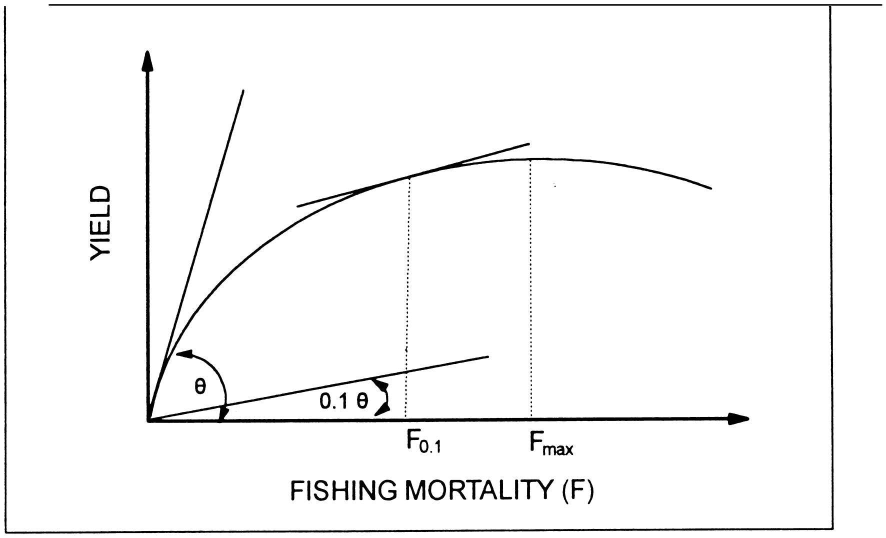

Fig. 2. Yield per recruit curve, showing the fishing mortality rate, F_{max}, corresponding to the maximum yield per recruit. Also illustrating the method of defining $F_{0.1}$ as the point on the yield per recruit curve at which the slope of the curve is 1/10 of the slope of the curve at the origin. Note $F_{0.1} < F_{max}$. (Excerpt from Caddy and Mahon 1995).

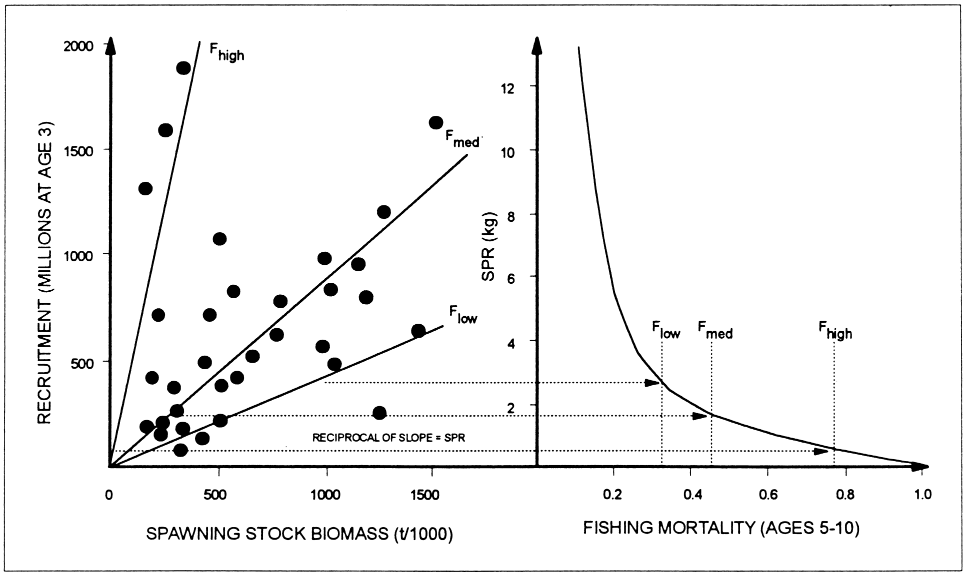

Fig. 3. Scatter plot of recruits versus spawning stock biomass (left) and spawning stock biomass per recruit curve (right). Illustrating the definition of F_{low}, F_{med} and F_{high} and their relationship to spawning stock biomass per recruit (SPR). (Excerpt from Caddy and Mahon 1995).

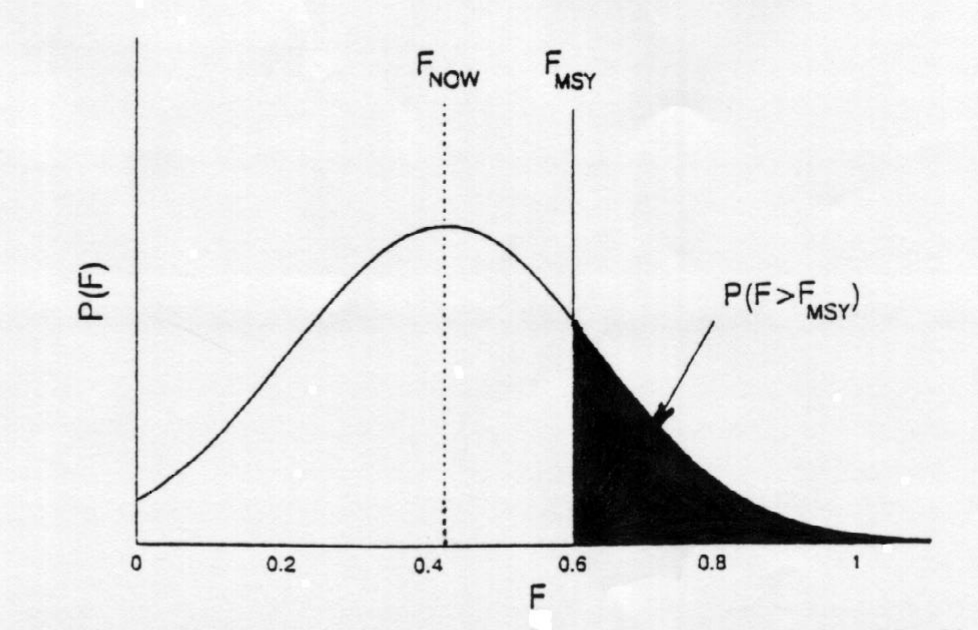

Fig. 4. Illustrating variance in the current best estimate of fishing mortality, F_{now}. Assuming F_{msy} as the LRP, the probability that F_{now} is larger than F_{msy} is represented by the dark right tail beyond F_{msy} (Excerpt from Caddy and McGarvey 1996).

Table 1. The reference points (RPs) described in this paper, data needs, modelling requirement, suitability for LRP or TRP, and bibliographic reference.

RPs	Definition	Estimation	Data Requirement	Suitability	Reference
Yt	Annual yield	$Y_t = Y_{t-1}(1 + g(B_{t-1} - B_{t-2})/B_{t-2})$	Catch of the previous year and Biomass (or biomass index) estimates for previous two years; g -- "feedback gain", a value of one or over seems to be precautionary.	TRP	Caddy 1998
MCY	Maximum constant yield that is estimated to be sustainable, with an acceptable level of risk, at all probable future levels of biomass.	MCY = $0.25F_{0.1}B_0$ (For a new fishery)	$F_{0.1}$ and B_0 (unfished biomass) If $F_{0.1}$ is not available, M may be used.	TRP	Annala 1993
MCY	as above	MCY = $0.5F_{0.1}B_{av}$ (Developed fishery)	$F_{0.1}$ and B_{av} (average historic recruited biomass). If $F_{0.1}$ is not available, M may be used.	TRP	Annala 1993
MCY	as above	MCY = 2/3MSY	MSY	TRP	Annala 1993
MCY	as above	MCY = cY_{av}	Y_{av} -- average catch over an appropriate time period c -- natural variability factor, ranges between 0.6 and 1.0.	TRP	Annala 1993

Z*	Upper limit for total mortality rate	$Z < Z^* = K\frac{L_\infty - L_m}{L_m - L_c}$	K and L_∞ (parameters of the von Bertalanffy equation). L_m – length at 50% maturity L_c -- length of first capture	LRP	Die and Caddy (1997)
L_c	Lower limit for length of first capture	$L_c > L_m - K\frac{L_\infty - L_m}{M}$	K, L_∞ and Lm (as above) M – natural mortality rate	LRP	Die and Caddy (1997)
MSY	Maximum sustainable yield	MSY = xMB_0	Natural mortality rate and unfished biomass. For LRP, x is set to be 0.2-0.3	LRP Or TRP	Gulland (1971), Beddington and Cooke (1983)
MSY	As above	Biomass Production modelling	Historical catch and effort data, catch and total mortality data, or catch, effort and area data.	LRP	Quinn and Deriso (1999)
E_{msy} or F_{msy}	Fishing effort or mortality rate corresponding to the MSY.	Biomass Production modeling	As above	LPR	Quinn and Deriso (1999)
MBP	Maximum biological production	Biomass Production modelling	Historical catch and total mortality data	LRP	Die and Caddy (1997)
Z_{mbp} or F_{mbp}	Total or fishing mortality rate corresponding to MBP	As above	As above	LRP	Die and Caddy (1997)

F_{max}	Fishing mortality rate corresponding to the maximum yield per recruit	Yield per recruit modelling	Natural mortality rate and growth	LRP	Quinn and Deriso (1999)
$F_{0.1}$	Fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of that near the origin.	as above	as above	TRP	Quinn and Deriso (1999)
$F_{\%SPR}$	Fishing mortality rate resulting in a certain percentage of the maximum spawning stock biomass per recruit in the stock.	Spawning stock biomass per recruit modelling	Natural mortality rate, growth and maturity at each age.	TRP or LRP	(Mace and Sissenwine 1993)
F_{med}	Fishing mortality rate allowing recruitment to be more than sufficient to balance the losses due to mortality in 50% of the time.	Spawning stock biomass per recruit modelling and a scatter plot of spawning stock biomass (or index) versus recruitment (or index)	as above plus historical information on recruitment (or index) and spawning stock biomass (or index)	TRP or LRP	Jakobsen (1992)
F_{low}	Fishing mortality rate allowing recruitment to be more than sufficient to balance the losses due to mortality in 90% of the time.	As above	as above	TRP	Jakobsen (1992)
F_{high}	Fishing mortality rate allowing recruitment to be more than sufficient to balance the losses due to mortality in 10% of the time	As above	As above	LRP	Jakobsen (1992)