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DYNAMIC POOL MODELS AND MANAGEMENT OF FISHERIES

by

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ABSTRAK

Dymanic pool models *secara eksplisit memperhitungkan beberapa faktor utama yang ikut berperan di dalam menentukan dinamika dari biomasa suatu populasi. Faktor-faktor tersebut ialah laju pertumbuhan, laju kematian yang disebabkan oleh baik proses alamiah maupun oleh kegiatan penangkapan, dan kemampuan berkembang-biak dari suatu kohort atau suatu kelas umur tertentu. Model ini terutama dikembangkan oleh BEVERTON dan HOLT (1957) yang mendasarkan teori mereka pada persamaan dinamika populasi dari RUSSELL (1931) dan dilengkapi dengan data komposisi umur yang terdapat di dalam suatu populasi Model BEVERTON dan HOLT ini mampu menentukan besarnya hasil tangkapan maksimum yang dapat dihasilkan oleh suatu kombinasi optimal dari besarnya laju penangkapan, ukuran atau umur minimum dari ikan yang boleh ditangkap, serta laju pertumbuhan dari masing-masing kelas umur yang membentuk suatu populasi.*

Seperti halnya dengan surplus production models, *model dari BEVERTON dan HOLT ini tidak terhindar dari kelemahan yang berasal dari anggapan bahwa populasi ikan senantiasa berada dalam keseimbangan. Di samping itu, asumsi lain bahwa tidak terjadi proses saling mempengaruhi di antara anggota populasi dan antar populasi satu dengan lainnya, akan memperbesar kelemahan yang telah ada sebelumnya. Dan lagi, keperluan akan data yang bersifat ekstensif dari penggunaan model BEVERTON dan HOLT ini di dalam analisa stok, akan memerlukan biaya yang tidak murah.*

Kontribusi utama dari model BEVERTON dan HOLT ini semata-mata tidak terletak pada penggunaan yang meluas atas rumus yang diciptakannya, melainkan terutama pada sumbangannya sebagai dasar dari pada teori-teori dinamika populasi modern yang dikembangkan sejak tahun delapan puluhan ini.

INTRODUCTION

Mathematical models applied to fish population have been classified into two major categories: dynamic pool models such as those of BARANOV (in RICKEIR 1975) THOMPSON and BELL (1934), RICKER (1954), and BEVERTON and HOLT (1957); and surplus production models such as those of HJORT *et al*. (in RICKER 1975), GRAHAM (1935), and SCHAEFER (1945, 1957).

The Characteristics of Dynamic Pool Models

In contrast to the surplus production models, the dynamic pool, analytic, or BEVERTON and HOLT model treats

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separately the factors of individual somatic growth rate, natural mortality rate, fishing mortality rate, and reproduction capability in influencing fish population biomass. Furthermore, the stock is represented in terms of its age structure, so that there are more explicit estimates can be built from the analytic model. As a consequent, it is usually more difficult to collect data for this model. The minimum data requirements for its application to a particular fish stock are time series of catch and effort data from the fishing on the stock, concurrent time series of age and size structure data from the catch, and age of first maturity from the stock.

The Dynamic Pool Model Concept of Maximum Sustainable Yield.

The goal of management of fisheries using a dynamic pool model is to determine the optimum harvesting strategy, i.e. determine the optimum combination of the amount of fishing (measured by fishing mortality, F), and age at which a cohort becomes vulnerable to fishing (measured by the age at first capture, t_c) which will produce the maximum sustainable yield from any particular age group structure and growth rate.

HARDY (1958) demonstrated clearly the consequences of considering age structure with regard to fishing mortality and age of entry as depicted in Table 1. For simplicity this example was assumed that the fishery was in a steady-state condition that only fishing mortality was operating. He plainly showed that 50 per cent of fishing rate could produce the same number of catch as 80 percent of fishing. Additionally, 50 percent fishing permits more older fish remain in population. In so far as older fish weigh more that younger ones, consequently, a greater yield in weight was demonstrated by the lower of the two fishing rates, i.e. 50 per cent of fishing rate. If age at first capture was put off to age three, the yield would increase and, conversely, the yield would tend to decrease when age at fisrt capture was delayed to much, later age, or if the fishing rate was too low. In conclusion, HARDY's example pointed out that there will be an optimum combination of fishing rate and age at first capture in the fishery that will produce the maximum yield from any particular age structure and growth rate of a population.

DERIVATION OF THE DYNAMIC POOL MODEL (BEVERTON AND HOLT MODEL)

The dynamic pool models, exemplified by the yield-per-recruit model developed by BEVERTON and HOLT (1957), is based on their origin to RUSSELL's population dynamics model (1931) and the development of well-defined age distribution from age determination. In addition, BEVERTON and HOLT assume a steady-state conditions in fisheries, i.e. the number of individual from a cohort during its life span is the same as the number of fish in all cohorts during any year, or in terms of yield, under steady-state conditions yield per generation equals to annual yield from an entire population (THOMPSON and BELL 1934; BEVERTON and HOLT (1957). We know for sure that the assumption of a steady-state stock is never strictly satisfied in real situations. However, fishery scientist are often in a condition that coerces them to set up assumptions, which they realize may be crude approximation to practical conditions. But, only by making such assumptions are we able to carry out the analysis of the kind of data commonly available, and at last, it is always better to do a coarse analysis than to do no analysis at all.

In contrast to the surplus production models, the dynamic pool models for yield analysis consider explicitly the factors of growth and mortality in influencing biomass. Actually, this type of analysis

Tabel 1. Annual catch in number and in weight at 50 per cent and 80 percent fishing rates from hyphotetical stock, based on cod.

Fishing Rate :	80% Annual		50% Annual			Catch (Yield in Weight)	
Age Group	Stock	Catch	Stock	Catch	Average Weight	80% Fishing	50% Fishing
1	1,000		1,000	–	–	–	–
2	200	800	500	500	82	65,600	41,000
3	40	160	250	250	175	28,000	43,000
4	8	32	125	125	283	9,056	35,000
5	2	6	62	62	400	2,056	24,800
6	–	2	31	31	523	1,046	16,213
7	–	–	16	16	–	–	–
8	–	–	8	8	–	–	–
9	–	–	4	4	–	–	–
10	–	–	2	2	–	– –	–
11	–	–	1	1	–	–	–
Totals	1,250	1,000	2,000	1,000		106,102	161,138

Source : From HARDY (1958).

stems from a mathematical model of the definition of the yield.

$$Y = \int_t F(1).\ N(t).\ w(t).\ dt \qquad (1)$$

where Y is yield, i.e. the portion of fish population harvested by human with its dimension of weight per unit time per unit area, F(t) is fishing mortality rate as a function of age with its dimension $(\text{year})^{-1}$, while N(t) and w(t) are the number and weight of individual fish at age t year respectively. In a simple way, yield can be described as the sum over time of the product of fishing mortality rate times the standing crops at any given time. Standing crops is the concentration of the population for a given area at a given point in time, which can be expressed as the number of animals, weight, or energy content at any particular time. Mathematically speaking, standing crop in weight at any given time is the product of the number of individual times the average individual weight at that moment.

In so far as any stock of fish is part of a complex natural system, it will be difficult to state with any certainty what the effects of any action on the stock will be. GULLAND (1983) argued that these uncertainties will be left behind when considering the fate of a cohort or a year-class of fish once they have been recruited to fishery. Among these uncerten-ties are the influence of adult stock size (density-dependet process) or the effects of environment on recruitment. Naturally, growth rate and natural mortality rate may still change, but after recruitment these changes are comparatively small. In its simple form, the BEVERTON and HOLT model does not take into account of the life cycle from eggs, larvae, juveniles, to recruitment. Graphycally, the fate of a cohort during its life span can be illustrated in Figure 1.

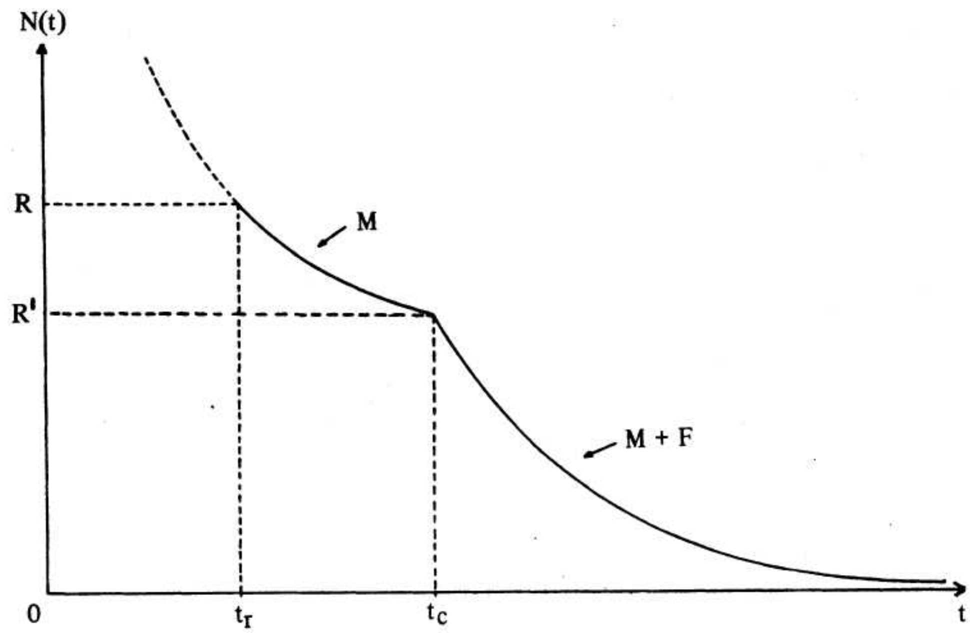

Figure 1. A basic model of cohort dynamics.
M and F are natural and fishing mortality rates respectively, t_r is age at recruitment, t_c is age at first capture. R is the number of recruits, R' is the number of individual at first capture.

In fish stock assessment theory it is generally assumed that, within any one cohort, the decline in numbers with age follows an exponential curve. Let R is the number of recruits entering the fishery at some age t_r. From age t_r through age t_c (the age at first capture) the cohort is subjected to the natural mortality rate, M, which is assumed to be constant througout the life span of the cohort. At time t_c, the cohort is assumed to be suddenly exposed to fishing mortality rate, F (knife-edge recruitment process), which then is assumed to remain stable for the rest of the cohort life. From Eq. (1) the expression for N (t) can be broken down into time periods concerning to age at recruitment, t_r, and age at first capture, t_c. Let N_o is the hypothetical number of individual that reach the hypothetical age 0 annually, then

$$R = N_0 e^{-M(t_r - t_0)} \qquad (2)$$

The number of individual at time t, where $t > t_r$ is

$$N(t) = Re^{-M(t - t_r)} \qquad (3)$$

while at time t, where $t_r < t_c < t$ the number of individual of the cohort is

$$N(t) = Re^{-M(t_c - t_r)} e^{-(F + M)(t - t_c)} \qquad (4_a)$$

or $$N(t) = Re^{-F(t - t_c) - m(t - t_r)} \qquad (4_b)$$

Let $R' = Re^{-M(t_c - t_r)}$, then the final expression of Eq. (4_a) becomes

$$N(t) = R'e^{-(M + F)(t - t_c)} \qquad (5)$$

where R' is the number of fish alive at time $t = t_c$.

To derive the mathematical expression for the BEVERTON and HOLT model let us take a look into catch equation. In the short interval from t to dt, the number of dC(t) and weight dY(t) that are caught will be given by,

$$dC(t) = F(t)\,N(t)\,dt \qquad (6)$$

$$dY(t) = F(t)\,N(t)\,w(t)\,dt \qquad (7)$$

and hence the total catch in numbers and weigh will be obtained by summing or integrating over the entire period the group of fish is exposed to the fishery, say from age t_c up to some limiting age t1.

$$C = \int_{t_c}^{t1} dC(t) = \int_{t_c}^{t1} F(t)\,N(t)\,dt \qquad (8)$$

$$Y \int_{t_c}^{t1} dY(t) = \int_{t_c}^{t1} F(t)\,N(t)\,w(t)\,dt \qquad (9)$$

Since natural mortality rate M is assumed constant, and fishing mortality rate is zero up to age at first capture t_c, and thereafter stable, therefore $F(t) = 0$ for $t \leq t_c$ and $F(t) = F$ = constant at $t > t_c$. By substituting N(t) of Eq. (5), the catch in number can be determined from Eq. (8)

$$C = \int_{t_c}^{t1} R'e^{-(F + M)(t - t_c)} F\, dt$$

Integration of this equation:

$$C = R' \left(\frac{F}{F + M} \right) \left(1 - e^{-(F + M)(t_1 - t_c)}\right)$$

or

$$C = R \left(\frac{F}{F + M} \right) e^{-M(t_c - t_r)} \left(1 - e^{-(F + M)(t_1 - t_c)}\right)$$

If t1, i.e. corresponding to the oldest age of fish in a fishery, is large, then the last terms can be ignored, becomes

$$C = R \frac{F}{F + M} e^{-M(t_c - t_r)}$$

or

$$C = \frac{F}{F + M} R'$$

The mean length of fish based upon the von BERTALANFFY growth model (1938) is

$$l(t) = L_{\infty}(1 - e^{-K(t - t_o)}) \qquad (10)$$

If the growth is isometric, the weight converted von BERTALANFFY growth equation can be expressed :

$$(w = a\, l^3)$$

$$w(t) = a(L_{\infty} (1 - e^{-K(t - t_o)}))^3$$

$$w(t) = W_{\infty} (1 - e^{-K(t - t_o)})^3 \qquad (11)$$

where W∞ is the asymptotic weight when t = ∞, w(t) is the weight at age t, L∞ is the asymptotic length when t = ∞, l(t) is the length at age t, and K is the growth parameter, t_o is the hypothetical age when length is equal 0. The right hand side of Eq. (11) can be expressed as

$$w(t) = W_{\infty}(1 - 3e^{-K(t-t_o)} + 3e^{-2K(t-t_o)} - e^{-3K(t-t_o)})$$

which can be more simply as

$$w(t) = W_{\infty} \sum_{n=0}^{3} U_n e^{-nK(t - t_o)}$$

where $U_O = 1$, $U_1 = -3$, $U_2 = 3$, and $U_3 = -1$.

Then, the yield can be formulated as

$$Y = \int_{t_c}^{t_1} F R e^{-F(t-t_o) - M(t-t_r)} W_{\infty} \sum_{n=0}^{3} U_n e^{-nK(t-t_o)}$$

Upon substitution with R'

$$Y = \int_{t_c}^{t_1} FR e^{M(t_c-t_r) - F(t - t_c) - M(t-t_r)} W_{\infty} \sum_{n=0}^{3} U_n e^{-nK(t-t_c)}$$

The integration

$$Y = F R' W_{\infty} \sum_{n=0}^{3} \frac{U_n}{F+M+nK} e^{-nK(t_c-t_o)} (1 - e^{-(F+M+nK)(t_1 - t_o)})$$

As the effect of the exact value of t1 in calculating yield is too small, it can be considerably simplified by assuming t1 = ∞, consequently, the yield equation becomes

$$Y = F R' W_{\infty} \sum_{n=o}^{3} \frac{U_n}{F+M+nK} e^{-nK(t_c - t_o)} \qquad (12)$$

As BEVERTON and HOLT express this results in terms of yield—per—recruit, then Eq. (12) becomes

$$Y/R = F e^{-M(t_c - t_r)} w\, W_{\infty} \sum_{n=0}^{3} \frac{U_n}{F+M+nk} e^{-nK(t_c - t_o)} \qquad (13)$$

where F is instantaneous rate of fishing mortality, assumed constant after $t > t_c$

M is instantaneous rate of natural mortality, supposed stable after $t > t_r$

R is number of recruits that enter the fishery at age t_r

W∞, K, and t_O are the von BERTALANFFY growth parameters

t_c is the age at first capture with given gear t_r is the age at recruitment to the fishery t1 is the maximum age attained in the stock.

A number of computer program exist for Eq. (13) and similar expression, besides, it is quite easy to operate with a programable calculator.

APPLICATION IN FISHERY MANAGEMENT

In management of fisheries, we are primarily concerned with changes on relative yield per recruit at different levels of fishing mortality rate or age at first capture. Fisheries administrations need advice on the likely results of changes from the current situation, for example, as a result of a regulation on mesh size, investment in more vessels, etc.

Three parameters in the yields-per-recruit equiation may controlled by managers, i.e. the rate of fishing mortality (F) by fishing effort regulation; age of entry into the fishable stock (t_c) by mesh size or hook size regulation; and in some situation, a regulatory agency may control the upper limit age of fish in the stock (t1).

With t_c, the BERTALANFFY's growth parameters (i.e. K, t_O, and W∞), and M held constant, there is generally a value of F which produces a maximum yield. This type of relationship can be illustrated in Figure 2.

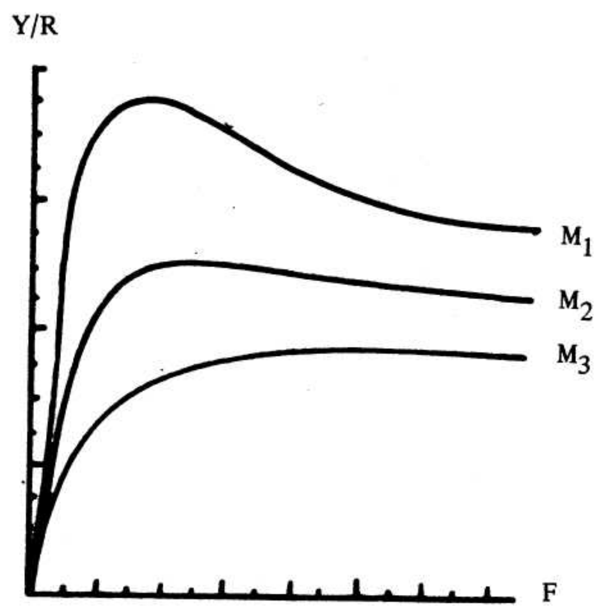

Figure 2. Yield per-recruit as function of fishung martality rate (F), as tc and age at first capture held constant (M1,M2,M3)

Analogously, age at entry into the fishable stock, t_c, has a similar type of relationship as depicted in Figure 3.

If the instantaneous rate of natural mortality is roughly estimated within a range of values, then a family of yield curves is generated, with lower Ms produce a smaller FMSY and a larger MSY per-recruit. The reason is that as if fishermen must compete with natural mortality upon fish, which implies that no individual fish will die caused by both natural mortality and fishing mortality rates simultaneously. The fishermen must catch the fish before the fish die from causes other than fishing. Consequently, a high natural mortality rate needs a high fishing rate for an optimum yield. This relationships are illustrated in Figures 2 and 3.

It is apparent that for a given different combination values of growth parameters, fishing mortality rate (F), and age at first capture (t_c) may produce the same yield-per-recruit. Plotting values of F versus t_c provides what is called a yield contours or isopleths diagram as showed by Figure 4. The actual shape of the BEVERTON and HOLT yield-per-recruit curves varies regarding to the relationship between growth rate and age at first capture.

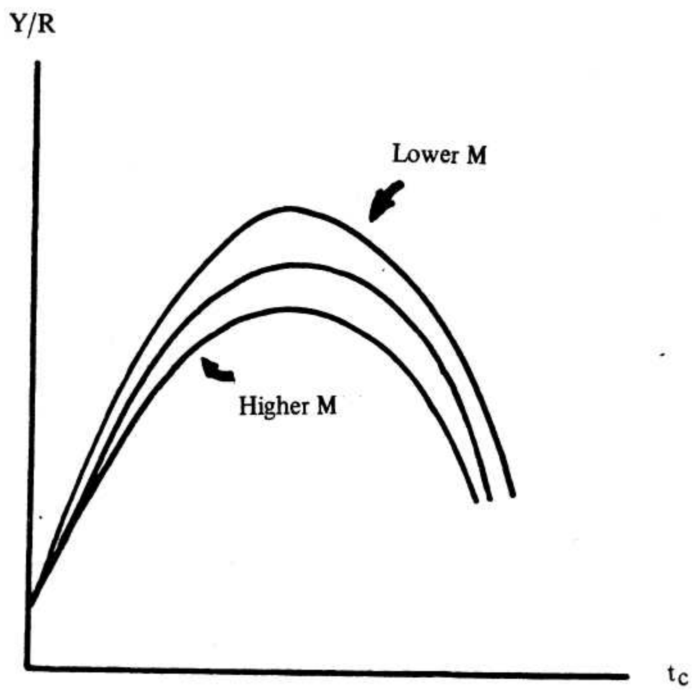

Figure 3. Yield per-recruit as a function of age at first capture (t_c), as F, rate of fishing mortality, held constant.

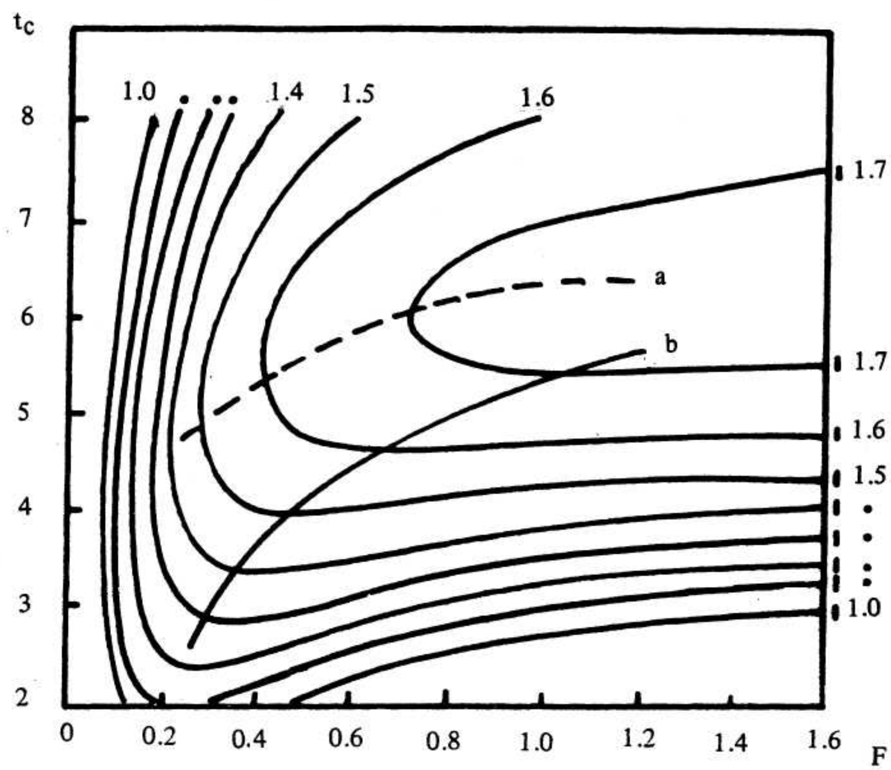

Figure 4. Yield per-recruit isopleth diagram as a function of age at first capture (t_c), and rate of fishing mortality (F).

The advantageous of creating the yield curves generated by BEVERTON and HOLT model is the capability to examine the effect of different mesh sizes in the gear used in the fishery, or the effect of different fishing effort in the fishery on the yield-per-recruit. For any given rate of fishing F, the maximum yield is determined by taking a vertical tangent line from F on one of the contour lines. For example, for F = 0.4, the vertical line is tangent to the isopleth of 1.6, approximately, and this point is obtained when t_c is between 5 and 6-year. The locus of all such tangents, i.e. line a in Figure 4, is termed by BEVERTON and HOLT as the line of eumetric fishing.

If there are no room to alter the mesh size of the fishing gear used in a fishery, i.e. t_c is effectively fixed, the maximum yield for any value of t_c (for example of 3-year) can be calculated by drawing a horizontal tangent line from t_c on one of the contours, in this case between 1.3 and 1.4 gram, approximately. The locus of the points of maximum yield from a given t_c is the line b in Figure 4.

A more general version of the BEVERTON & HOLT yield-per-recruit model of Eq. (13) was developed (BEVERTON and HOLT 1966), which especially suitable for assessing the effects of the characteristics of the fishery, such as the amount of fishing that can be conveniently expressed as the ratio of fishing to natural mortality rates ($\frac{F}{M}$), or the exploitation ratio, E (= $\frac{F}{Z}$), and the relative size of first capture, conveniently expressed as

$$C = \frac{l_c}{L_\infty} = 1 - e^{-K(t_c - t_o)}$$

Hence we can write

$$e^{-K(t_c - t_o)} = 1 - C$$

and

$$e^{-M(t_c - t_r)} = e^{-M(t_o - t_r) - M(t_c - t_o)} = e^{-M(t_o - t_r)} (1-c)^{M/K}$$

so that Eq. (13) can be written as

$$Y/R = FW_\infty \, e^{-M(t_o - t_r)} (1-c)^{M/K} \sum_{n=0}^{3} \frac{U_n}{F+M+nK} (1-C)^n$$

or by taking out the constant terms

$$Y/R = E(1-C)^{M/K} W_\infty \, e^{-M(t_o - t_r)} \sum_{n=0}^{3} \frac{U_n \, (1-C)^n}{1 + \frac{nK}{M} (1-E)} \qquad (14)$$

Eq. (14) is considered as a function of E (i.e. the measure of fishing intensiity) and C (i.e. size at first capture) with M/K as the only parameter. A yield-isopleth diagram can be directly generated by using a wide range of values of M/K, C, and F which have been tabulated by BEVERTON and HOLT (1966). From the expression of the yield-perecruit in Eq. (14), the effects of different actions on the fishery can be simply determined.

ESTIMATION OF EQUILIBRIUM YIELD

As an example of estimating the equilibrium yield-per-recruit, let us use the data of the *kurisi,* threadfin bream *(Nemipterus marginatus),* in North Borneo (PAULY 1984) with its constant parameters estimated as follows:

K = 0.37 per year	t_c = 1.0 year
t_O = -0.2 year	t_r = 0.4 year
$W\infty$ = 286 gram	M = 1.1 per year

Calculation can most conveniently started from a conventional integer number of recruits at age t_r say of 1000 recruits; the yield equation Eq. (12) can be used, and gets

$$Y = F \times 1000 \times e^{-1.1(1.0 - 0.4)} \times 286 \left(\frac{1}{F + 1.1} - \frac{3e^{-0.37(1.2)}}{F + 1.47} + 3e^{\frac{-2(0.37)(1.2)}{F + 1.84}} - e^{\frac{-3(0.37)(1.2)}{F + 2.21}} \right)$$

By evaluating this equation for a range of F- values enable us to calculate the maximum sustainable yield of the threadfin bream per 1000 recruits. For example, for F = 1 0 then the yield per-recruit will be 7.3 grams, for F = 1.5 will be 7.8 grams, and so fort. By calculating various F—values, the maximum sustainable yield-per-recruit is found 7.9 gram that corresponds to the optimum fishing mortality of F = 2.3

CONCLUSIONS

The dynamic pool models contain an explicit description of each of the main factors that control the responses of the stock against exploitation. As a result, these models are able to provide a relatively comprehensive discription of stock behavior. Furthermore, these models can express an empirical relation regarding with the relationship between the number of potentially mature fish in the stock (i.e. the breeding stock size) and the number of new recruits entering to the fishable stock (stock recruitment relationship).

Though the fishermen are more interested in physical absolute yield than to relative yield per recruit, but, absolute yields are not necessarily required, if the objective of the management is to determine the optimum harvesting strategy based on the effects of changes in fishing effort or size at fist capture.

Unfortunately, the minumum data requirements for such models are extensive so that assessment cost are relatively expensive. Type of information and source of data can be described as follows (SHUTER and KOONCE 1984):

i) a consistent index of abundance, i.e number of individual for each group, which can be derived from data of catch, effort, gear type, age and size compositions.

ii) estimates of age-specific rates of exploitation, i.e. fraction of biomass taken by fishery per unit time, these information may be optained from mark-recapture study, catch, and age or size compositions.

iii) estimates of mean size at age.

iv) estimates of mean age at first maturity.

v) estimates of relative reproductive potential of all age groups.

A major criticism of the dynamic pool models as well as the surplus production models is the treatment of the species under consideration as if were living in a steady-state conditions, and in an isolated single species systems which no interaction among species exist. In addition, absolute yield is diretly proportional to yield per recruit over a wide range of fishing mortality only if recruitment of juveniles seems to be independent of spawning stock size over a wide range of stock sizes (PAULY 1984; JONES 1984).

An interesting concept based upon the dinamic pool models which has had wide application in fishery management, especially in the Northwest Atlantic areas, is a target of fishing mortality F0.1. This strategy limits fishing mortality rate F to the value which correspoding to 1/10 of the marginal increase of yield per recruit at very low levels of F (GULLAND and BOEREMA 1973). Graphically, this concept of F0.1 can be illustrated in Figure 5.

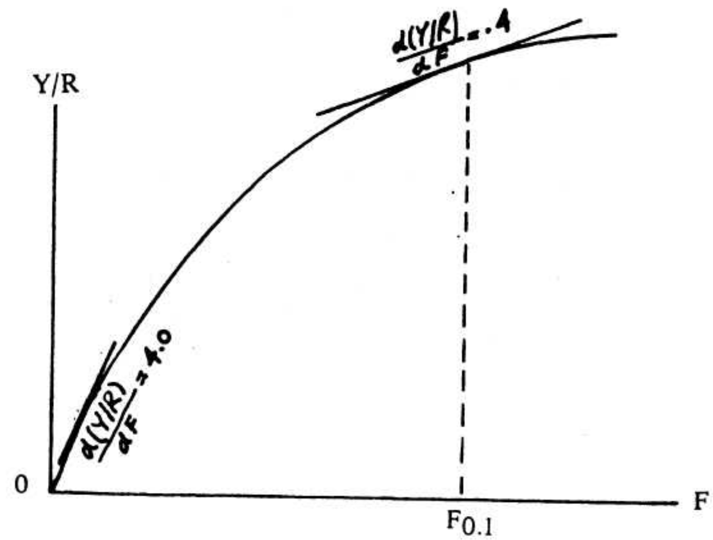

Figure 5. F_O 1 is the value of F Corresponds to 1 /10 of the marginal increase in yield per-recruit at low level of F.

In 1980's the main contributions of the BEVERTON and HOLT model can be noticed, primarily, in providing the fundamental principle for modern population analysis models, rather than in the worldwide application of the specific form of the model they have created.

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