Application of Yield-per-Recruit and Surplus Production Models to Fishery Enhancement Through Juvenile Releases

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ABSTRACT

Yield-per-recruit and surplus production models are modified for use when hatchery-reared juveniles are released into a fishery. The yield-per-recruit model indicates that species with low ratios of natural mortality to growth and high asymptotic weight offer the greatest potential weight yield per stocked juvenile. The Ricker surplus production model is easily modified to express catches as functions of fishing effort and numbers of juveniles released. Thus the model can be used to estimate the effectiveness of stocking a fishery with hatchery releases based on a time series of catch, stocking, and effort data. The model can also be used as a simulation tool.

The release of hatchery-reared juveniles to enhance fisheries for a number of species is practiced in Japan and to a lesser degree in other countries, including the United States and Norway (Yatsuyanagi 1982, Botsford and Hobbs 1984, Isibasi 1984, Ulltang 1984). When juveniles are released to augment a natural stock that is the basis of an existing fishery, stocking combines extensive mariculture with traditional fishery science. New quantitative tools are needed to evaluate and manage this system. The simple stocking vs. harvesting ratios that are used to evaluate and manage aquaculture no longer apply in the presence of varying fishing pressure and a natural stock. For example, fishing mortality often increases as stocking levels increase, making it difficult to attribute any increase in yield solely to the increase in stocking. However, traditional fishery production models are also inadequate since they do not incorporate stocking as a variable. Although some models have been developed to examine the effects of stocking relative to hatchery cost and the return to the fishery, these analyses have not taken into account other management variables including size limits and fishing effort (e.g., Oshima 1984). More sophisticated models have been developed which can be used to simulate the effects of stocking or develop optimal fishery policy, and can be applied in situations where the biology of the resource is well known and estimates of age-specific population parameters are available (Watanabe et al. 1982, Botsford and Hobbs 1984, Ulltang 1984, Watanabe 1985).

In this paper the traditional Beverton and Holt (1957) yield-per-recruit model and the nonequilibrium Ricker surplus production model (Ludwig and Walters 1985), both standard tools for fishery management, will be modified so that they can be applied to evaluate and manage fisheries in which juveniles are released. The yield-per-recruit model can be applied with very little modification to juvenile releases to evaluate the yield-per-released-juvenile as a function of the biological parameters (growth and mortality) and management parameters (release size, size at entry, and fishing mortality). The contribution of the released juveniles to the spawning stock can be evaluated in a similar fashion by computing the spawning-stock biomass per released juvenile. The Ricker surplus production model can be modified to express the catch as a function of effort and stocking so that a time-series of stocking, catch, and effort data can be analyzed to evaluate the effectiveness of stocking and to estimate maximum sustainable yield in the presence of juvenile releases.

Yield-per-recruit models

The Beverton and Holt (1957) yield equation can be formulated as a function of the ratio of instantaneous mortality to von Bertalanffy growth (M/K), the ratio of length at recruitment to the fishery to asymptotic length (c), the ratio of fishing mortality to natural mortality (F/M), and the ratio of length of the stocked juvenile to the asymptotic length (a).

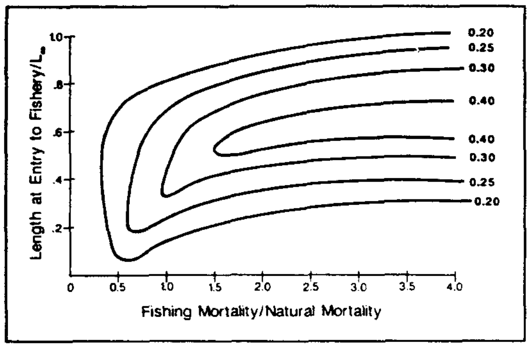

Figure 1
Yield per stocked juvenile for *Pristipomoides filamentosus* as function of relative length of entry and relative fishing mortality. Estimates of $M/K = 1.7$, $W_\infty = 8.5$ kg taken from Ralston (1981); size of release taken as 0.1 L_∞.

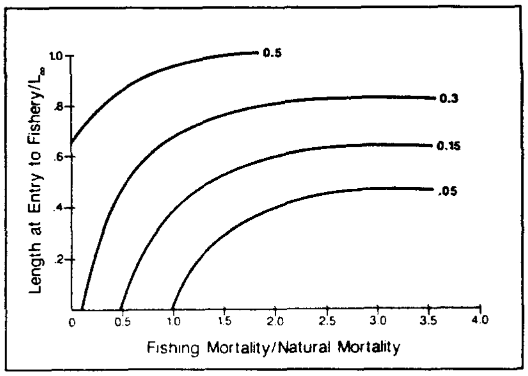

Figure 2
Spawning-stock biomass (kg) per stocked juvenile for *Pristipomoides filamentosus* as function of relative length of entry and relative fishing mortality. Estimates of $M/K = 1.7$, $W_\infty = 8.5$ kg taken from Ralston (1981); size of onset of sexual maturity taken as 0.5 L_∞; size of release set at 0.1 L_∞.

Under this formulation the yield (Y) per stocked juveniles (S) is:

$$Y/S =$$
$$(M/K)(F/M)((1-c)/(1-a))^{(M/K)}(1/(M/K+(F/M)(M/K))$$
$$-3(1-c)/(1+(M/K)+(F/M)(M/K))$$
$$+3(1-c)^2/(2+(M/K)+(M/K)(F/M))$$
$$-(1-c)^3/(3+(M/K)+(F/M)(M/K)).$$

In a similar fashion, the spawning-stock biomass can be expressed as a function of the same variables plus the ratio of the length at onset of sexual maturity to the asymptotic length (Beddington and Cooke 1983).

Based on these formulations, just as in the traditional yield-per-recruit analysis, the yield-per-stocked juvenile (*Y/S*) and the contribution of the stocked juvenile to the spawning stock biomass (*SSB/S*) can be calculated as functions of *F/M* and *c* (Figs. 1,2). The value of the yield per stocked juvenile varies considerably with *c* and *F/M*, so the proper choice of *F/M* and *c* is necessary to maximize the benefit from stocking. For example, in Figure 1, when the length of entry to the fishery is 50% of the asymptotic length, a hatchery-released juvenile opakapaka, *Pristipomoides filamentosus*, contributes 0.3 kg to the fishery when fishing mortality equals natural mortality; whereas when fishing mortality increases to 1.5 natural mortality, at the same size of entry, the contribution to the fishery of a hatchery-released juvenile opakapaka will increase 33% to 0.4 kg. The *SSB/S* isopleths indicate the contribution of a stocked juvenile to the population spawning-stock biomass. For example, for the snapper (opakapaka) when $F/M = 1.5$ and $c = 0.5$, a stocked juvenile will contribute 0.15 kg to the population spawning-stock biomass (Fig. 2). If the spawning-stock biomass of the population is known, the *SSB/S* equation can estimate the number of juveniles needed to be released to increase the population spawning-stock biomass to a given level. The *SSB/S* and *Y/S* equations, together with the hatchery costs and the value of the harvested fish, can serve to evaluate the economic benefits of the release programs as functions of variables *c*, *a*, *M/K*, and *F/M*.

Hatchery technology and knowledge of the early-life history of marine organisms have made it possible to rear numerous marine organisms. The *Y/S* and *SSB/S* equations permit comparisons of the benefits from stocking among species with different population parameters. For example, there are three commercially important species in Hawaii that might be candidates for hatchery release programs: Mahimahi, *Coryphaena hippurus*; a snapper, *P. filamentosus*; and a spiny lobster, *Panulirus marginatus*. The *Y/S* isopleths were computed for each of these species, and the maximum values of *Y/S*, for all *c*, as a function of *F/M*, were determined. These maximum values of *Y/S* are plotted for the three species (Fig. 3). The differences between the three species in their contribution to the fishery are striking. For example, when fishing mortality is equal to natural mortality and the size at entry to the fishery is optimal, a released spiny lobster will contribute 0.02 kg to the fishery, a released snapper will contribute 0.3 kg, and a released mahimahi will contribute an amazing 2.5 kg. Even when price per kilogram is considered and the possibility that only 25-50% of adult mahimahi remain around the islands, the mahimahi releases appear to offer high economic return. The contribution of a released mahimahi to the fishery is so much greater than that of the snapper, and in turn the contribution of a snapper is greater than that of the spiny lobster, largely because of differences in the *M/K* ratio (1.0 for mahimahi, 1.7 for snapper, and 3.0 for lobster) and the asymptotic weight (30 kg for mahimahi, 8.5 kg for snapper, and 1.7 kg for spiny lobster). The lower the ratio of natural mortality to growth, the greater the survival of the released individual; and the

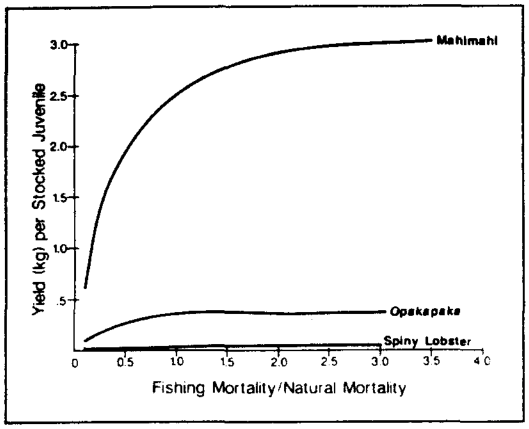

Figure 3
Maximum yield per stocked juvenile as a function of relative fishing mortality for mahimahi, opakapaka, and spiny lobster. Parameter estimates for mahimahi $M/K = 1.0$, $W = 30$ kg (Uchiyama et al. 1986); for opakapaka $M/K = 1.7$, $W = 8.5$ kg (Ralston 1981); for spiny lobster $M/K = 3.0$, $W = 1.7$ kg (Polovina unpubl. data).

greater the asymptotic weight, the greater the weight gained by the released individual. The SSB/S follows the same order for the three species as Y/S. Thus among the candidates for juvenile release, those with low M/K ratios and high asymptotic weights will offer the greatest contribution in biomass to the fishery.

Fishery production models with stocking

The most frequently used production models, Schaefer and Gulland-Fox, do not explicitly specify a recruitment relationship, and hence do not easily lend themselves to modification to include hatchery releases. However, the Ricker model for surplus production (Ludwig and Hilborn 1983) is a simple production model which can easily handle stocking. The Ricker model for surplus production is expressed by the following three equations (Ludwig and Walters 1985):

$$B_{t+1} = S_t \exp(A - BS_t + U_t) \qquad (1)$$

$$S_t = B_t - C_t \qquad (2)$$

$$C_t = B_t(1 - \exp(-qE_t)) \qquad (3)$$

where B_t is the population biomass in year t, S_t is the biomass remaining after harvest in year t, C_t represents the catch in year t, E_t denotes the effort in year t, U_t represents independent normally distributed random variables with mean 0 and variance v, and A, B, and q are parameters estimated from catch and effort data.

To modify these equations to include H_t hatchery-released juveniles in year t before harvesting, it is necessary to express the biomass in year $t+1$ resulting from H_t. A power function relationship

$$B_{t+1} = a(H_t)^b$$

with parameters a and b appears appropriate for hatchery releases of Oregon coho salmon (Peterman and Routledge 1983). For a fast-growing species the major contribution from stocking to the fishable biomass will occur in the same year as the stocking, and thus H_{t+1} rather than H_t would be used in the power function equation.

If the biomass from the hatchery-released stock is simply added to that of the natural stock in the first equation of the Ricker model for surplus production, then we obtain:

$$B_{t+1} = S_t \exp(A - BS_t + U_t) + a(H_t)^b. \qquad (4)$$

This modified equation, together with the two other equations of the Ricker model, produces a production model which incorporates hatchery releases. The contribution of the hatchery releases will increase the catch directly through Equation (3) and those that are not caught will increase S_t through Equation (2).

The Ricker surplus model without stocking shows the usual dome shape in which production first increases then decreases ultimately to zero with increasing fishing mortality (Fig. 4). When a fixed number of hatchery releases are added to the system, the yield curve has the usual dome shape as a function of fishing mortality; but rather than declining to zero, as is the case of an unstocked population, the yield approaches an asymptotic yield of $a(H_t)^b$ with increasing fishing mortality (Fig. 4). The relative contribution of the releases to the fishery will be greatest for relatively high levels of fishing mortality. Hatchery releases can increase the maximum yield and the corresponding level of optimum fishing effort.

If hatchery releases occur in the absence of a natural population the Ricker model with stocking just reduces one equation:

$$C_t = a(H_t)^b \ (1 - \exp(-qE_t)).$$

Unfortunately, due to the nonlinear nature of the Ricker surplus production model, it is not as easy to estimate the parameters as, for example, for the Schaefer model. A complete approach to parameter estimation for the Ricker model is presented in Ludwig and Hilborn (1983). Here a simplified approach will be presented for the Ricker model with stocking when it is assumed that the fishing effort is measured without error. First, assume a value for q and compute B_t and C_t from Equations (2) and (3). Then estimate A, B, a, and b from Equation (4) with the nonlinear regression, using the B's and S's obtained from the previous step. Finally, vary q and repeat the previous steps until the sums of squares of the nonlinear regression are minimized. Computer programs for nonlinear regression can typically be used as a basis for this parameter estimation approach.

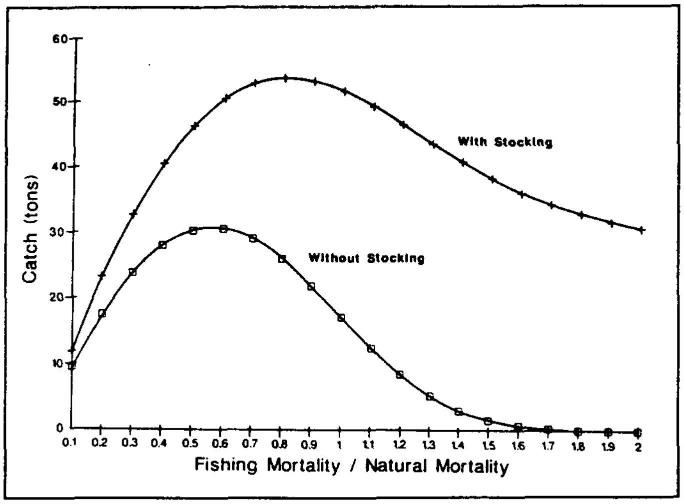

Figure 4

Equilibrium Ricker surplus production model with and without stocking. Curve without stocking based on biomass model $B = S \exp(0.7 - 0.007S)$; curve with stocking based on $B = S \exp(0.7 - 007S) + 25$.

An experimental approach to stocking can be an efficient means of evaluating the effectiveness of stocking and identifying optimal stocking levels, but simulation of any design is a necessary first step before implementation. For example, releasing juveniles into a fishery on alternating years and then comparing catches in years *with* stocking to catches in years *without* stocking may be considered a way to estimate the effectiveness of stocking. This experimental design can be simulated with the stocking surplus production model (Fig. 5). Suppose a population has a carrying-capacity biomass of 100 t and is fished with a fishing mortality of $F = 1.0$. Suppose juveniles are released in a quantity which contributes 20 t to the fishable biomass over a 10-year period on years 2, 4, 6, 8, and 10, and no releases occur in years 1, 3, 5, 7, and 9. The stocking surplus production model estimates that equilibrium fishing with $F = 1.0$ results in a catch of about 49 t annually. The first stocking (year 2) increases the catch to 62 t, and then the catch follows an oscillating sequence of lower catches during years *without* stocking and higher catches during years *with* stocking. The oscillating sequence has an increasing trend over time as the stock biomass grows due to stocking. At some point an equilibrium would be reached and the sequence would oscillate between the same two levels of catch. However, the use of this design to estimate the effectiveness of stocking by comparing catches between years with and without stocking would underestimate the effectiveness of stocking at this level of fishing mortality, since the catches do not return to their prestocking level between years of stocking.

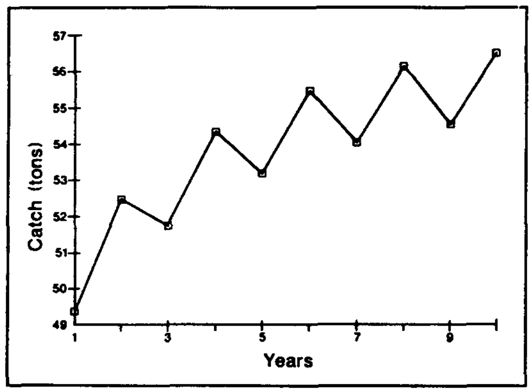

Figure 5

Simulation of yield with $F = 1.0$ when stocking occurs on even numbered years. Parameters of the Ricker surplus production model with stocking are: $A = 1.2$, $B = 0.007$, $a(H_t)^b = 20t$.

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