

# BIOECONOMIC EVALUATION OF THE CULTURE/STOCKING CONCEPT FOR CALIFORNIA HALIBUT

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## ABSTRACT

We describe development of a model used to evaluate the bioeconomics of culture for stocking of the California halibut, *Paralichthys californicus*. Results from this model provide guidance for future research and preliminary estimates of feasibility. The model mimics growth of a cohort in culture from postlarvae to release, then in the ocean from release to mortality from natural causes or the fishery. Costs of culture and the benefits of cultured fish to the fishery are calculated. The latter are given in terms of number of released fish caught, biomass caught per release, cost per fish caught, and net benefit per released fish. The cost of post-larval fish is shown to be a substantial part of culture costs and should be reduced if possible. We demonstrate a graphical method for determining the release time that minimizes cost per recruit. For current parameter values this value is about 300 d. Both culture costs and optimal release time are sensitive to costs of food and space. We graphically show the trade-off between high growth rate and high costs of culture feeds. The cost of producing a recruit depends on post-release survival rate, but is not as sensitive as expected because of a compensatory shift in optimal release age. Costs per released fish caught could be near \$5/fish if natural growth rates could be achieved in culture and the culture period could be extended to 300 d.

## INTRODUCTION

In 1984 the Ocean Resources Enhancement Program (OREHP) began research to develop the biological and physical means to culture and stock California halibut, *Paralichthys californicus*, for fisheries enhancement. In addition to the biological research on culture and early life history (Gadomski et al. 1990), development of the culture/stocking concept required concurrent economic evaluation. On the basis of past experience, we began this kind of evaluation in the early stages of this project even before all of the data necessary to establish economic feasibility had been obtained. Although the ultimate goal of our economic evaluation was to determine feasibility and optimal management policy, the main purpose of our early evaluation was to guide research and planning.

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We developed the mathematical models necessary for economic evaluation and performed the economic analysis possible with currently available data. We did this by developing several computer programs based on these models and incorporating available data into them. We then provided these models to other OREHP researchers so that they could continue the economic evaluation as additional data became available. These models will enable them to continue to evaluate the culture/stocking concept as research progresses by refining estimates of parameter values in the models and conducting further analysis. For information about the programs themselves see Appendix B.

Although the ultimate general goal of the evaluation is to determine economic feasibility (or at least to project the total costs of culture and benefits of stocking), other specific goals have been important in the early stages of the project. The primary purposes of the initial model were: (1) to evaluate dynamic behavior (i.e. to get an idea of how the system "works"), (2) to establish which of the needed pieces of information were available and which were outstanding, (3) to evaluate sensitivity of net benefits to unknown or poorly known parameters, and (4) to obtain a rough idea of the costs of culture and stocking.

We first present the relevant background on California halibut. This is a review of what is known about the life history, existing fisheries, and culture of these and related species. We then describe the models used in the computer programs that were developed to evaluate culture and stocking of this species. These use parameter values from the background section. Finally we present results of analyses using these programs and discuss their economic implications.

## FISHERY AND CULTURE BACKGROUND

Development of a model of the culture, stocking, and fishery systems requires a review of available information. In this section, we describe existing information on life history, the fisheries, and culture performance for the California halibut. Information available on culture performance is limited; hence, some parameters from other similar species that have been cultured are used.

### Life History and Fisheries

The California halibut supports both commercial and sport fisheries in southern California (Figure 1). It is fished in California and in Mexico and has experienced well-documented declines in catch leading to concern about the health of the stocks. The U.S. commercial catch reached a peak of 4.7 million pounds in 1919 and declined to 0.26 million pounds in 1971. Since then there is some evidence of a recovery. It is not known whether this is a result of the more restrictive regulations or due to natural fluctuations in abundance or availability (Methot 1983). For a more complete historical perspective see Barsky (1990).

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## Commercial and Recreational Catch: California Halibut

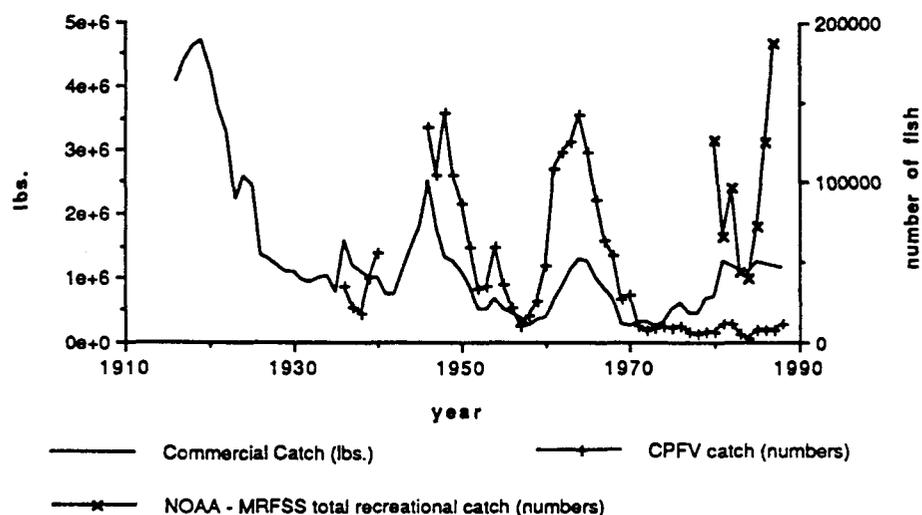


FIGURE 1. History of the California halibut fisheries. The solid line is the total harvest by commercial fishermen. The + 's are the harvest by commercial passenger fishing vessels. The X's are total harvests by sport fishermen.

The commercial fishery for California halibut has traditionally been primarily an otter trawl fishery but, in recent years, entangling nets have dominated the catch (Methot 1983). Since 1911 the use of otter trawls has been restricted in nearshore waters in southern California (Clark 1931). In 1971, regulations were enacted that allowed trawling within 3 mi of shore in the Santa Barbara Channel area. These same regulations established a minimum mesh size of 7.5 inches, a minimum size limit of 4 lb for commercially caught halibut, and season closures during the spawning season (Karpov 1981).

The sport fishery for California halibut is primarily a hook-and-line fishery that has operated from commercial passenger fishing vessels (CPFVs), man-made structures, shorelines, and private boats. The gear used is specialized and there is little incidental catch of other species. Since the late 1960s, CPFVs have not been able to profitably target on California halibut, and the proportion of the sport catch taken by private boats has increased (Methot 1983). Recently a sport fishery involving SCUBA gear and pole spear or spear gun has developed (C.A. Pattison, California Department of Fish and Game, pers. comm.). For a more complete historical description of the recreational fishery see Oliphant (1990) and Helvey and Witzig (1990).

In spite of the long history and the economic importance of this fishery, relatively little is known about the life history of California halibut. They spawn at depths of 6–20 m during the winter and spring, with the greatest frequency occurring from February to May. The larvae and postlarvae are pelagic (Frey 1971; Plummer et al. 1983; Lavenburg 1987). Young fish are common in embayments where they are believed to remain through the early juvenile

phase, but it is not known whether the larvae settle in bays or migrate there after settlement (Plummer et al. 1983). The size distributions of fish caught in embayments and in shallow coastal waters suggest that juvenile halibut can reside in bays for a period of 2–3 years, reaching sizes there up to 30 cm standard length, but that most migrate to sea when they reach a length of about 20 cm (Frey 1971; Haaker 1975; Barry and Cailliet 1981; Kramer and Hunter 1987; Kramer 1990; Hammann and Ramirez-Gonzalez 1990). Males may begin to mature when they are in their second year, females 1 to 2 years later, and all fish are probably mature when they are 5 or 6 years old (Frey 1971). California halibut may live as long as 30 years and attain weights up to 23 kg (Frey 1971).

Growth patterns of the California halibut have been reported in terms of length-at-age data and length-weight data. Length-at-age has been reported by Hulbrock (1974) for males ages 1 through 19 years and females ages 1 through 18 years, by Frey (1971) for females ages 1 through 12 years, and by Haaker (1975) for males and females ages 1 to 3 years. The three data sets appear to be consistent, so the data from Hulbrock were used to describe growth. We fit von Bertalanffy growth equations to the length-at-age data to obtain

$$L_t = 1130 [1 - e^{(-0.1234 t - 0.1114)}] \quad (1a)$$

for males and

$$L_t = 1440 [1 - e^{(-0.118 t - 0.0852)}] \quad (1b)$$

for females where  $L_t$  is total length in millimeters at age  $t$  years. The length-weight relationship for both sexes was determined by regression of Hulbrock's data to be

$$W_L = 7.811 \times 10^{-6} L^{3.048} \quad (2)$$

where  $W_L$  is weight in grams at length  $L$  in millimeters. Reed and MacCall (1988) report parameter estimates similar to these.

The growth rate of juvenile fish during the first 2 years is less well known. A linear growth rate with intercept set at the initial post-larval size and the slope chosen so that size at 1 year corresponds to the von Bertalanffy growth equations for the California halibut population (analysis of data from Hulbrock 1974), would lead to a slope of 0.061 cm/d. However, the slope of the von Bertalanffy growth equation itself at 1 year is lower, 0.030 cm/d for males and 0.038 cm/d for females. Kramer and Hunter (1987, 1988) report a growth rate of 0.033 cm/d (10 mm/month from laboratory studies) and a size of 150 mm in bay/lagoon habitats at 9 months post settlement (0.039 cm/d). Growth of halibut in Todos Santos Bay fit a line with a slope of 9.51 cm/year and an intercept at 8.98 cm for ages 1 through 7 which indicates a growth rate of 0.051 cm/d during the first year and 0.026 cm/d in subsequent years (Hammann and Ramirez-Gonzalez 1990).

Adult mortality rates have not been directly estimated for California halibut. Reed and MacCall (1988) used a method based on the longevity of the species (cf. Hoenig 1983) to estimate the average annual instantaneous total mortality rate to be 0.15/year. This method is biased low depending on sample size (Hoenig 1983). In their analysis of the California halibut fishery, Reed and

MacCall (1988) used the values 0.1 and 0.2/year. The natural mortality rate for Pacific halibut, *Hippoglossus stenolepis*, off the coasts of Washington, British Columbia, and Alaska has been reported as 0.31/year, but this estimate may be biased upward because of loss of tags from fish used in these studies (Myhre 1967). The Pacific halibut used to estimate mortality rates were larger than the average size of the California halibut and so would be expected to have lower natural mortality rates (if mortality were due to predation). However, because of the potential bias in the estimate of mortality for Pacific halibut, 0.3/year is a reasonable upper limit for the natural mortality rate of adult California halibut. This value is consistent with values for similar species (Pauly 1979).

Mortality rates of juvenile halibut differ from those of adults but are similarly poorly known. Annual instantaneous mortality rates for a similar species, the speckled sanddab, *Citharichthys stigmaeus*, were estimated by Ford (1965). He estimated mortality rates both from the rate of decrease in density and directly from the age structure in 1962 and 1963. Because his age-structured estimates assume that recruitment has been constant, we have used only the estimates from the rate of decrease in density. The averages of the annual instantaneous mortality rates corresponding to the monthly percent survival reported by Ford are 2.286, 0.624, and 1.080/year for fish of age 0, 1, and 2, respectively. All three age classes of sanddabs are smaller than 1-year-old California halibut, thus the halibut would be expected to have lower mortality rates at age. In view of the paucity of mortality rate estimates for California halibut, we use a range of natural mortality rates in our economic evaluation.

### Culture Performance

The information required to develop a model of the culture system comes from several sources. Biological information on culture of this species is relatively scarce, hence we have had to rely in part on information from other cultured species. Information on the components of the physical plant and their costs are also occasionally borrowed from other culture schemes.

The biological information needed for aquaculture is a description of how the organism responds to the environment provided in the culture system. In particular this would be growth, survival, food and oxygen consumption, waste production, and subjective criteria such as fitness for stocking or condition of flesh. Ideally each of these could be fully described over a range of environmental parameters such as temperature, oxygen levels, and feeding rates that affect the cultured species. Some of this information has been and is being developed within the OREHP project—in particular, information on the maintenance of spawning stock and growth and survival of the egg, larval, and juvenile stages. For older life history stages, information has been limited to observations of growth of captured individuals and growth data incidental to other experiments which may not reflect the potential growth rate of cultured fish. This presents a significant limitation to the precision of a detailed model, because costs are sensitive to growth rate. Preliminary estimates of parameters such as food conversion rates and tolerances for minimum dissolved oxygen levels and maximum ammonia concentrations have been taken from culture systems for similar species.

For many species, the aquaculture environment is adjusted so that growth rate is greater than that observed in the natural environment. Stephens et al.

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(1988) in Table 7 of their annual report indicate growth rates of 0.019 and 0.028 cm/d for the first 97 d after hatching of California halibut at approximately ambient temperatures (16° C) and elevated temperatures (28° C) respectively. These growth rates are somewhat lower than estimates for the wild population but include the metamorphosis to the juvenile form during which the fish changes its shape significantly. Captured individuals raised in the laboratory yield similar growth rates (0.026 cm/d, Kaupp 1989 and 0.025 cm/d, Innis 1990) when raised over several years. The juvenile growth rates eventually attainable in an aquaculture system may be higher when the environmental requirements of the larval and juvenile stages are better known.

The nutritional energy requirements of fish can be partitioned into two categories: growth and maintenance. Maintenance requirements include basal metabolism and activities such as movement and feeding. For fish the caloric requirement for maintenance is commonly considered to be a power function of weight with the exponent falling between 0.6 and 0.8 and a coefficient dependent on activity level and body temperature. We have used a value of 0.69 for the exponent (from Townsend and Calow 1981, p. 27), and .05 kilocalories (kcal)/d for the coefficient in the power function. Schmidt-Nielsen (1979, p.186) gives a value of 0.001 kcal/h for poikilotherms at 20° C (for body weight in grams). However, this is a minimum estimate; active swimming can increase energy expenditures significantly. For the purpose of this model we have assumed a level twice the minimum.

In rapidly growing fish a large portion of the diet is used in growth. In aquaculture, growth is often expressed in terms of conversion efficiency, kilocalories of fish produced per kilocalorie of food. Food conversion efficiencies for cultured fish vary depending on species, feed type, and culture system. Typically, values of 1:3 or 1:4 (Bardach et al. 1972, p. 12) are considered to be very good. Reported values often include maintenance requirements. We use 1:3 in our standard model runs so that for each kilocalorie equivalent of weight gain the fish must be fed three times that many kilocalories of food. This is added to the energy required for maintenance to determine total food kilocalories in a time interval.

Oxygen requirements of cultured fish can be calculated using a mass balance equation by assuming that all food that is not converted to tissue is oxidized. Approximately 0.275 g of oxygen are required to metabolize each kilocalorie of food. Aeration requirements can be calculated as the difference between the available dissolved oxygen and this requirement. A value of 6.75 mg oxygen per liter is recommended as a minimum level that should be maintained for nonanadromous marine species (Poxton and Allouse 1982).

The most important waste product in this culture system will be ammonia. The effect of ammonia on the fish is dependent on temperature and pH because ammonia is only toxic in the unionized form. The unionized portion is sensitive to pH, being about 1% of total ammonia at a pH of 7 and 10% at a pH of 8 (Allen et al. 1984, p. 163). We have assumed an intermediate value of about 5% which corresponds to a pH of about 7.5. Increasing levels of ammonia first begin to inhibit growth, then at higher concentrations lead to mortality. For example, growth of Dover sole, *Solea solea*, and turbot, *Scophthalmus maximus*, were unaffected by unionized ammonia concentrations of around 0.1 mg/L, but levels of 0.3–0.9 mg/L prevented all growth (Poxton and Allouse

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1982). Brownell (1980) found values of 24-h LC50 near 0.4 mg/L and values that inhibited first feeding  $> 0.1$  mg/L for marine fish larvae of several species. Setting the unionized ammonia tolerance at 0.1 mg/L yields a total allowable ammonia concentration of 2.0 mg/L.

Waste products are removed from a culture system with the waste water that flows out of the tanks. In a fish culture system, ammonia concentrations can be calculated using a mass balance equation involving the excess nitrogen in the feed (above that consumed by growth) and the inflow and outflow rate of water (Allen et al. 1984). Water flow rates can then be set so that ammonia is removed from the system at the same rate that it is produced while maintaining the ammonia concentration in the tank below the critical concentration.

The composition of the food and the feeding rate affect growth and mortality rates directly but also determine the waste levels in the culture unit which affect the aeration requirement and water flow rate. A cost effective food composition should balance the nutrition requirements of the fish against the costs of waste removal and is necessarily species and culture system specific. We have limited the food composition parameters in the model to caloric content and ammonia equivalent. The feeding rate is calculated to satisfy the caloric requirements for growth and maintenance. We have arbitrarily set the feed parameters at an energy content of 5 kcal/g and an ammonia equivalent of 32 mg/g; these values are equivalent to a feed composed of 20% fat, 20% protein, and the rest carbohydrate (cf. Deniel 1976; Kuhlman et al. 1981).

The density of fish in the culture unit and the size and shape of the units affect growth and mortality rates in a complex and subtle manner. Optimal rearing densities are often dependent on poorly understood interactions such as the shape and water flow patterns of the tanks, the possibility of disease transmission, and species-specific behavioral patterns such as schooling, individual spacing, and cannibalism. Flat fish require a large benthic surface which places some constraints on the size and shape of the tanks. We have arbitrarily assumed the tanks to be 20,000 L; this corresponds to a tank 1 m deep by 6 m in diameter that is kept  $3/4$  filled. We have used tilapia and trout as representative of species for which densities have been optimized. Tilapia have been successfully reared at densities of 50 g/L of water (Ballerin and Haller 1982) and trout are reared at densities in excess of 10 g/L (cf. Leitritz and Lewis 1976). The number of tanks required is calculated to satisfy the biomass density criterion during the time step.

### CULTURE AND FISHERY MODELS

To evaluate culture and fishery independently, then combine results, we divided the life history of a cultured, then stocked, fish into two phases. The point dividing these phases had to be greater than the maximum size to which fish would be cultured and less than the lower size limit of the current fishery. We chose this point somewhat arbitrarily to be 24 cm, which is a size at which the juveniles have typically left the nearshore environment. We refer to fish above this size as being in the potentially fishable population, and when we use the word "recruitment" we mean recruitment to this population. We stress that this is a somewhat arbitrary dividing point, and its exact value, as long as it is

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greater than the maximum culture size and less than the lower size limit in the fishery, will not affect the cost/benefit analysis. This separation results in three consecutive periods in the life history of a cultured, then stocked, fish: the culture phase, post-release phase, and post-recruitment phase (Figure 2). The first phase covers the period from hatching to release. The second phase covers the period from release to the size of recruitment into the potentially fishable population (24 cm), and the third covers the period from that size through adulthood and possible capture in the fishery. The specific release size can vary from post-larval size (i.e. no juvenile culture) to the size of recruitment into the fishable population (24 cm). During the time between release and the recruited size, fish are assumed to be in the "juvenile habitat" and are subject to different growth and mortality rates than after the recruited size when they are assumed to have adult growth and mortality rates.

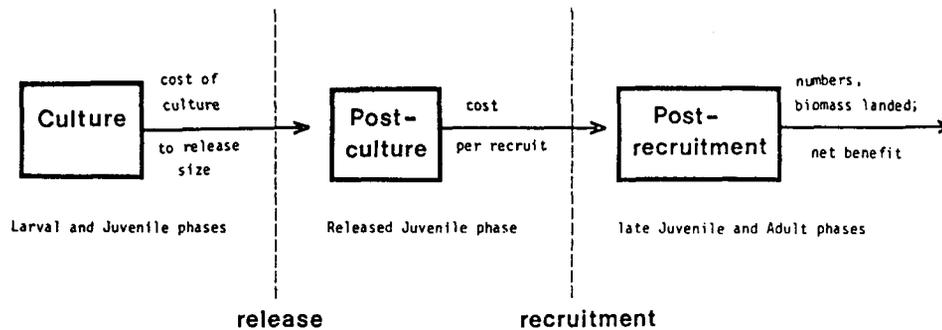


FIGURE 2. A schematic of the culture/release process as described in the computer programs for economic evaluation.

### Culture System Model

The model of the culture system has been developed to provide a means of examining the economics of culture based on the limited information presently available. The culture system model consists of three submodels: biological, physical, and economic (cf. Allen et al. 1984). The biological submodel defines the behavior of the fish in the environment of the culture system. The physical submodel is a description of the physical plant itself and the necessary inputs, and the economic submodel calculates the costs associated with running the culture system. The model is calculated iteratively. Each iteration represents a time step (usually 7 or 10 d) and begins with the growth of the fish. Then, using the growth, present size, and the environmental requirements of the fish, the necessary physical plant is sized and inputs are calculated. Finally, the costs are totaled to complete the iteration. The model is structured in this way to allow extrapolation of limited data for analysis over a wide range of size classes.

#### *Biological Submodel*

The biological model calculates growth and mortality during each time step. Growth in length is calculated as a function of time. We have used a linear model for increase in length so that,

$$L_{t+1} = L_t + (g_c \times \delta_t) \quad (3)$$

with  $L_0 = L_m$

where

$L_t$  = length at time t

$L_m$  = initial length

$g_c$  = daily growth rate in the culture system

$\delta_t$  = time interval.

For our baseline model we have used approximately the estimated wild population growth rate (cf. Hammann and Ramirez-Gonzalez 1990) of  $g_c = 0.05$  cm/d and an initial length of  $L_m = 2.5$  cm.

Weight is calculated using the length-weight relation for the natural populations

$$W_t = w_c \times L_t^{w_e} \quad (4)$$

where

$W_t$  = weight at time t

$w_c$  = weight-at-length coefficient

$w_e$  = weight-at-length exponent

In our model we used the values given above computed from Hulbrock's (1974) data. Weight gain is the difference between weight at the beginning and end of the time step.

$$\delta_w = W_{t+1} - W_t = \text{weight gain per fish per time step} \quad (5)$$

We use an exponential survival function so that

$$N_{t+1} = N_t \times \exp(-m \times \delta_t) \quad (6)$$

where

$N_t$  = number of fish at time t

$m$  = mortality rate per day

In the baseline model the mortality rate  $m = 0.005/d$ .

### *Physical Submodel*

The environmental variables—food, water flow rates, aeration requirement, and tank numbers—are calculated to meet the minimum caloric requirements for growth and maintenance, as well as maintain required dissolved oxygen levels, ammonia concentration and biomass density of fish.

The caloric requirements per time unit are partitioned into a growth requirement and a maintenance requirement that includes both basal metabolism and active swimming (Allen et al. 1984). Total food is calculated to meet these two needs as

$$F_t = \frac{(\delta_w \times k_b \times r_f) + (\delta_t \times b_c \times W_t^{be})}{k_f} \quad (7)$$

where

$F_t$  = weight of food required per fish per time step

$k_b$  = kilocalories per unit of fish biomass

$r_f$  = food conversion rate, kilocalories of fish gain per kilocalorie of food

$b_c$  = maintenance coefficient

$b_e$  = maintenance exponent

$k_f$  = kilocalories per unit of food.

Using a mass balance equation, we calculate the oxygen required to metabolize all of the food, minus the amount which becomes fish biomass. It is

$$O_{2t} = [(F_t \times k_f) - (\delta_w \times k_b)] \times 0.275 \text{ g/kcal} \quad (8)$$

where

$O_{2t}$  = oxygen requirement per fish per time step

0.275 g/kcal = the amount of oxygen required to metabolize a specified amount of food.

The latter ratio (oxygen to energy) is for a hypothetical food which is 50% fat and 50% carbohydrate and protein by energy content. This constant is chosen conservatively so that the oxygen requirements of most common diet mixtures will be met. A higher fat content would require a higher rate but not greater than 0.30 g/kcal.

Ammonia production is also calculated from a mass balance equation as the amount of ammonia in the food, less that which becomes fish flesh. It is

$$NH_{3t} = (f_t \times n_f) - (\delta_w \times n_b) \quad (9)$$

where

$NH_{3t}$  = ammonia produced in time step t

$n_f$  = grams of ammonia per gram of food

$n_b$  = grams of ammonia per gram of biomass.

This assumes that all the nitrogen in food is excreted as ammonia or in a form that is converted to ammonia in the tank system. Because not all of the nitrogen is excreted as ammonia, it is a conservative (high) estimate.

For this evaluation, we have assumed a flow-through system with no water treatment. Water flowing through the system adds dissolved oxygen and removes ammonia. Flow rates must be set to provide a specified safe level of ammonia, but the additional required amount of oxygen can be met through aeration. Regardless of whether the tanks are aerated, the flow rate must be sufficient to prevent the ammonia concentration from exceeding a critical level. Flow per fish is

$$H_2O_t = \frac{NH_{3t} \times 2.0}{NH_{3c}} \quad (10)$$

where

$H_2O_t$  = total water required per fish in time step t

$NH_{3c}$  = maximum allowable ammonia concentration.

Because of the variable nature of ammonia excretion due to noncontinuous feeding and incomplete mixing of water, we have included a safety factor of 2.0.

If the tanks are aerated,  $H_2O_t$  is the required flow rate per fish. If the tanks are not aerated, the dissolved oxygen in the inflowing water is assumed to be the primary source of dissolved oxygen in the system. The aeration deficit is calculated as

$$O_{2d} = \text{minimum} [H_2O_t \times (O_{2in} - O_{2c}) - (O_{2t} \times 2.0) \text{ or } 0.0] \quad (11)$$

where

$O_{2d}$  = deficit in grams of dissolved oxygen per fish per time step

$O_{2in}$  = dissolved oxygen concentration in inflowing water

$O_{2c}$  = minimum allowable dissolved oxygen concentration

minimum = function which selects the minimum of two values.

We have again included a safety factor of 2.0 to allow for the effects of imperfect mixing and nonconstant usage. If the oxygen deficit is zero, the flow necessary to remove the ammonia is satisfactory for the oxygen requirement as well. A nonzero oxygen deficit must be met by increasing the inflow of water, so that

$$H_2O_t = \frac{O_{2t} \times 2.0}{O_{2in} - O_{2c}}$$


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The number of tanks required is based on a maximum biomass density criterion, so that

$$T_t = \frac{N_t \times W_t}{d_c \times t_v} \quad (13)$$

where

$T_t$  = number of tanks required at time  $t$

$d_c$  = maximum allowable density

$t_v$  = tank volume.

### *Economic Submodel*

The cost per individual entering the fishery is the total cost to raise a cohort divided by the number of that cohort that survive to enter the fishery. The total cost is the sum of the accumulated costs for food, electricity, water, and space. These are calculated on a per time step basis as the fish grow from post-larval size. We have not included economies of scale or discounting of future value.

The cost of food per time step for the cohort is

$$C_{ft} = F_t \times N_t \times P_f \quad (14)$$

where

$P_f$  = price per unit of food (\$/kg).

The cost of electricity per time step for the cohort is

$$C_{et} = \frac{(H_2O_t \times N_t \times H_2O_e)}{(T_t \times T_e)} \times P_e \quad (15)$$

where

$H_2O_e$  = electrical use per unit water (pumping)

$T_e$  = electrical use per tank (lights, aeration, circulation pump)

$P_e$  = price per unit of electricity (dollars/kwh).

The cost of water per time step for the cohort is

$$C_{H_2O_t} = H_2O_t \times N_t \times P_{H_2O} \quad (16)$$

where

$P_{H_2O}$  = price per unit of water (treatment, prorated pumps and piping).

The total capital cost during a time step is proportional to the number of tanks used during the time step, so that

$$C_{Tt} = T_t \times P_T \quad (17)$$

where

$P_T$  = price per tank per day (maintenance, labor, and prorated tank, building, and accessories).

The total accumulated cost of culturing a cohort up to age  $t$  is

$$C_{At} = C_{At-1} + C_{ft} + C_{et} + C_{H_2O_t} + C_{Tt}, \quad (18)$$

beginning with the initial cost of the cohort (as either postlarvae or eggs),

$$C_{A0} = N_0 \times P_{pl} \quad (19)$$

where

$P_{pl}$  = price per postlarva or egg.

Electrical use is calculated as that required to pump the total water flow 10 m vertically plus a fixed amount for lighting and aeration of tanks. The prices and parameter values are listed in Table 1.

### Post-Release, Pre-Recruitment Model

The total accumulated cost of the cohort at age  $t$  is the total cost per stocked fish if the cohort is stocked at that age. However, the cost per recruit (24 cm) depends on the rate of survival to 24 cm as well as cost per stocked fish. The survival rate to recruitment depends on the time required to grow to the minimum entry size (24 cm) and the size-specific survival rate during that time. To describe post-release growth, we have used the linear growth model which is equivalent to growing the fish from post-larval size to the size at 1 year in the natural population over the span of 1 year, so that

$$t_L = \frac{L_r - L_t}{g_n} \quad (20)$$

where

$t_L$  = time to reach the fishery

$L_r$  = minimum length in the fishery (size at recruitment)

$L_t$  = length at time of release

$g_n$  = linear growth rate for the natural population.

For the baseline model we use the approximate estimated natural growth rate of juveniles (0.05 cm/d). We have assumed the mortality rate is a linear function of length in this phase. Because growth is linear, the rate is equal to the rate for the mean size during the time period prior to entering the fishery, so

$$m_L = m_p + \left[ \left( \frac{L_t + L_r}{2} - L_p \right) \left( \frac{m_r - m_p}{L_r - L_p} \right) \right] \quad (21)$$

TABLE 1. Parameters and baseline values for culture system model.

Symbol	Parameter	Baseline value
$L_m$	Initial length, length of postlarva	2.50 cm
$g_1$	Growth rate	0.050 cm/d
$\delta_t$	Time interval per time step	10 d
$w_c$	Coefficient for length to weight function	0.00872
$w_e$	Exponent for length to weight function	3.048
$m$	Mortality rate per day	0.005
$k_b$	Kilocalories per unit of fish biomass	1.3 kcal/g
$r_f$	Food conversion rate, kcal of fish gain per kcal of food	0.30
$b_c$	Coefficient in basal maintenance function	0.05
$b_e$	Exponent in basal maintenance function	0.69
$k_f$	Kcal per unit of food	5.0 kcal/g
$n_f$	Ammonia concentration in food	0.032 g NH <sub>3</sub> /g
$n_b$	Ammonia per gram of fish biomass	0.016 g NH <sub>3</sub> /g
NH <sub>3c</sub>	Maximum allowable ammonia concentration	0.10 mg/L
O <sub>2in</sub>	Dissolved oxygen concentration in inflowing water	8.0 mg/L
O <sub>2c</sub>	Minimum allowable dissolved oxygen concentration	6.75 g O <sub>2</sub> /L
$d_c$	Maximum allowable biomass density	50.00 g/L
$t_v$	Volume of tanks	20000 L
$P_f$	Price per unit of food	\$ 1.00/kg
H <sub>2</sub> O <sub>e</sub>	Electrical use per unit of water	0.03 kwh/1000 L
$T_e$	Electricity used per tank	7.0 kwh/tank/d
$P_e$	Price per unit of electricity	\$ 0.10/kwh
P <sub>H<sub>2</sub>O</sub>	Price per unit of water	\$ 0.00/1000 L
$P_T$	Prorated price per tank per day	\$ 3.50/tank
$N_0$	Initial number of post-larval fish	100,000
$P_{pl}$	Price per post-larval fish	\$ 0.15/postlarva
$L_r$	Length at recruitment	24.00 cm
$g_n$	Linear growth rate for the natural population	0.05 cm/d
$m_r$	Instantaneous yearly mortality rate at recruitment	0.3/year
$m_p$	Instantaneous yearly mortality rate at post-larval size	7.0/year

where

$L_p$  = length of post-larval fish

$m_L$  = average mortality rate for fish growing from  $L_t$  to  $L_r$

$m_r$  = instantaneous yearly mortality rate at size of recruitment

$m_p$  = instantaneous yearly mortality rate at post-larval size

For the mortality rate at post-larval size we use  $m_p = 7.0/\text{year}$ , and for the mortality rate at recruitment we use  $m_r = 0.3/\text{year}$ , the baseline value of natural mortality of adult fish.

The survival rate for the period from stocking to recruitment into the fishable population for fish of size L is

$$S_L = \exp(-m_L \times t_L) \quad (22)$$

and the cost per fish stocked at time t that will actually reach recruitment is

$$C_{rt} = \frac{C_{at}}{S_L \times N_t} \quad (23)$$

### Post-Recruitment, Fishery Model

The post-recruitment fishery model must describe the bioeconomic dynamics of stocked fish after recruitment to the potentially fishable stock so that the economic benefit of the culture/stocking program can be evaluated. These dynamics depend on individual growth and mortality, as well as how the fishery is managed (i.e. the size limit and mortality due to fishing; c.f. Botsford and Hobbs 1984). Because yearly fishing mortality rates are poorly known and we may wish to examine possible benefits of changes in management, we evaluate the benefits of stocking over a range of fishing mortality rates and size limits. We consider here only a single fishery. This can be thought of as the combined recreation and commercial fishery. For a more detailed analysis of the catch distribution among multiple users with use-specific regulations, see Reed and MacCall (1988).

The impacts of stocking on the fishery can be separated into two areas: the direct, short-term impact and the indirect, long-term impact. The former includes effects of stocked fish entering the fishery and the latter includes the effects of descendants of stocked fish entering the fishery. Because prediction of the indirect, long-term impacts requires knowing the processes that control recruitment, we concern ourselves here with only the direct, short-term effects.

Several aspects of the post-recruitment dynamics are of potential economic interest. The most obvious characteristic is fishery catch per stocked fish both in numbers and in biomass. These depend only on post-recruitment growth and mortality rates, however, and do not reflect culture costs. Another way of looking at the post-recruitment effects of stocking, therefore, is in terms of the cost per fish caught. To account for the size and value of the fish caught, a fourth way of evaluating stocking is in terms of net value (gross value minus cost) of fish caught, assuming gross value of a fish is proportional to weight.

The model assumes that yearly mortality rates (both fishing and natural) are constant and that growth follows a von Bertalanffy curve. The number of recruits at any age past recruitment is

$$N_t = N_0 \times S_t \quad (24)$$

where

$N_t$  = number of fish at time t

$N_0$  = number of fish at time 0 (recruitment or age 1)

$S_t$  = portion surviving from recruitment.

---

Survival prior to entering the fishery is given by

$$S_t = \exp(-m \times t) \quad \text{for } t \leq t_c \quad (25)$$

where

$m$  = instantaneous yearly natural mortality rate

$t_c$  = time at which fish reach the minimum size limit.

We use an intermediate value of 0.2/year as a baseline for our analysis here but also evaluate the sensitivity of the results to a range of values from 0.1 to 0.3/year. Botsford et al. (1989) presented results for a more conservative analysis using a mortality rate of 0.3/year. After the age of entry into the fishery

$$S_t = \exp[-(m \times t) - (f \times [t-t_c])] \quad (26)$$

where

$f$  = instantaneous yearly fishing mortality rate.

Catch per recruit is the fraction of recruited, stocked fish (numbers) caught in the fishery. This is calculated as

$$C_r = \frac{f}{m + f} \times \exp(-t_c \times m). \quad (27)$$

Biomass yield per recruit is the average weight increase in the total catch per recruited, stocked fish (biomass). The yield is calculated by numerical integration from

$$Y_r = \frac{f}{m + f} \int_0^{\infty} S_t W_t dt \quad (28)$$

where

$W_t = a_1 \times L_t^{b_1}$  = weight in kilograms at time

$a_1$  = the coefficient in the length-weight relationship

$b_1$  = the exponent in the length-weight relationship

$L_t = a_2 \times [1 - \exp(-b_2 \times [t - c_2])] =$  length in cm.

For the parameters in the von Bertalanffy growth equation ( $a_2$ ,  $b_2$ , and  $c_2$ ), we used values estimated from Hulbrock's (1974) data.

Culture cost per fish caught is calculated as

$$P_f = \frac{P_r}{C_r} = \frac{\text{cost per recruit}}{\text{catch per recruit}} \quad (29)$$

and net benefit of yield per recruit is

$$B_r = (p_k \times Y_r) - P_r = \begin{array}{l} \text{value of yield per recruit} \\ \text{- cost per recruit} \end{array} \quad (30)$$

where

$p_k$  = value per unit weight of fish to the fishery  
in \$ /kg

$P_r$  = cost per recruit, obtained from the culture cost model.

## RESULTS

Our analysis thus far is limited by the results available from culture research. We have developed an understanding of the dynamics of the culture/stocking system (i.e. how the system "works") and a preliminary estimate of culture costs and benefits. We have also identified aspects of the system to which costs are particularly sensitive and used these sensitivity analyses to evaluate results from biological experiments. The third category can be useful in planning future research. Cost or benefit figures should be considered preliminary at this stage.

### Culture

The simplest view of how a culture system would work can be obtained by following the development of a cohort of fish as they grow through culture (Table 2). As the fish increase in size, the number of tanks required increases even though the number of fish declines because of mortality. Costs per time step increase as the fish increase in size and metabolic demand, and the total cost of culture per fish begins with the cost per postlarva and increases to higher values. For purposes of determining the sensitivity of culture costs to changes in the system due to further research, it is valuable to know the distribution of costs. Early in culture the costs of post-larval fish dominate total costs, but they constitute a lower proportion relative to costs of food, labor, and the physical system as fish are cultured longer (Figures 3 and 4).

### *Optimal Size of Release*

A critical open question with regard to the culture/stocking system is how long the fish should be cultured before being released. Shorter culture time will incur less culture costs, but fewer fish will survive after release to be fishable recruits. The number that survive depends on juvenile mortality rate which decreases with age and size of the fish. Consequently, there is a tradeoff between the increased cost of larger fish and the decreased survival of smaller fish (Figure 5; see Table 1 for parameter values). As the possible release size increases, both the cost per fish released and the fraction that would survive to recruitment size increase, but at different rates. The cost per recruit is the cost per fish released divided by the survival to recruitment (23)]. This value initially declines, then increases, and the optimal size of release is the minimum of this curve. For example, Figure 5 indicates that to minimize overall cost per cultured

TABLE 2. Culture plant simulation program.

Age (days)	Average length (cm)	Total dry weight of food fed per day	Daily costs during time step	Survival from initial post-larval stock	Number tanks required	Average weight
0	2.50	0.000	4.20	1.000	1	0.142
10	3.00	0.013	6.84	0.951	1	0.248
20	3.50	0.018	7.71	0.905	1	0.397
30	4.00	0.024	8.65	0.861	1	0.596
40	4.50	0.031	9.65	0.819	1	0.854
50	5.00	0.039	10.70	0.779	1	1.178
60	5.50	0.048	11.77	0.741	1	1.574
70	6.00	0.058	12.87	0.705	1	2.053
80	6.50	0.069	13.97	0.670	1	2.620
90	7.00	0.080	15.07	0.638	1	3.284
100	7.50	0.093	16.17	0.607	1	4.052
110	8.00	0.106	17.25	0.577	1	4.933
120	8.50	0.121	18.30	0.549	1	5.935
130	9.00	0.136	19.33	0.522	1	7.064
140	9.50	0.153	20.33	0.497	1	8.329
150	10.00	0.170	21.29	0.472	1	9.739
160	10.50	0.189	22.21	0.449	1	11.301
170	11.00	0.208	23.09	0.427	1	13.022
180	11.50	0.228	23.92	0.407	1	14.912
190	12.00	0.250	24.71	0.387	1	16.977
200	12.50	0.272	25.45	0.368	1	19.226
210	13.00	0.295	26.15	0.350	1	21.668
220	13.50	0.319	26.79	0.333	1	24.309
230	14.00	0.345	27.39	0.317	1	27.159
240	14.50	0.371	27.94	0.301	1	30.225
250	15.00	0.398	28.44	0.287	1	33.515
260	15.50	0.426	33.09	0.273	2	37.038
270	16.00	0.455	33.50	0.259	2	40.801
280	16.50	0.486	33.86	0.247	2	44.813
290	17.00	0.517	34.18	0.235	2	49.082
300	17.50	0.549	34.45	0.223	2	53.616
310	18.00	0.582	34.68	0.212	2	58.423
320	18.50	0.616	34.87	0.202	2	63.512
330	19.00	0.652	35.02	0.192	2	68.890

Release size to minimize cost per rec. = 17.00 cm  
 Release age to minimize cost per rec. = 290.00 days  
 Cost per released fish at optimum = 0.89557549 \$/release  
 Minimized cost per recruit = 1.52805835 \$/recruit

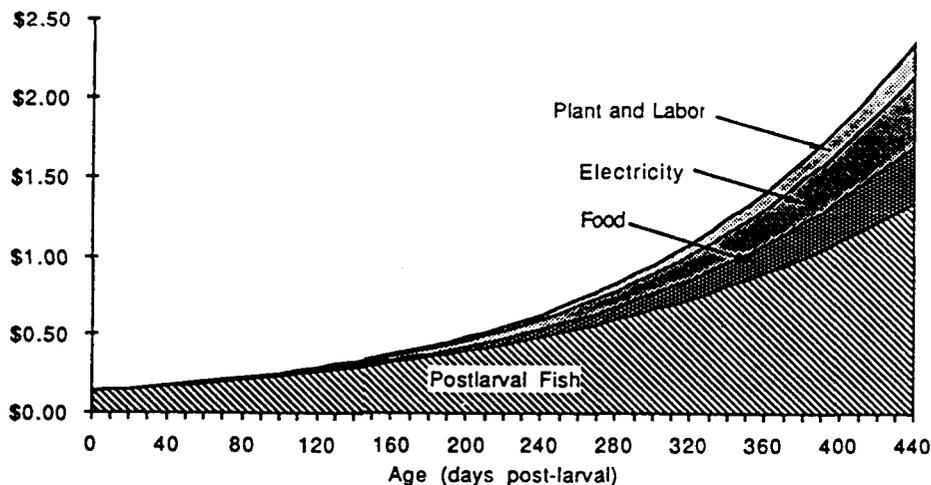


FIGURE 3. Distribution of costs per released fish by age at release in terms of actual value.

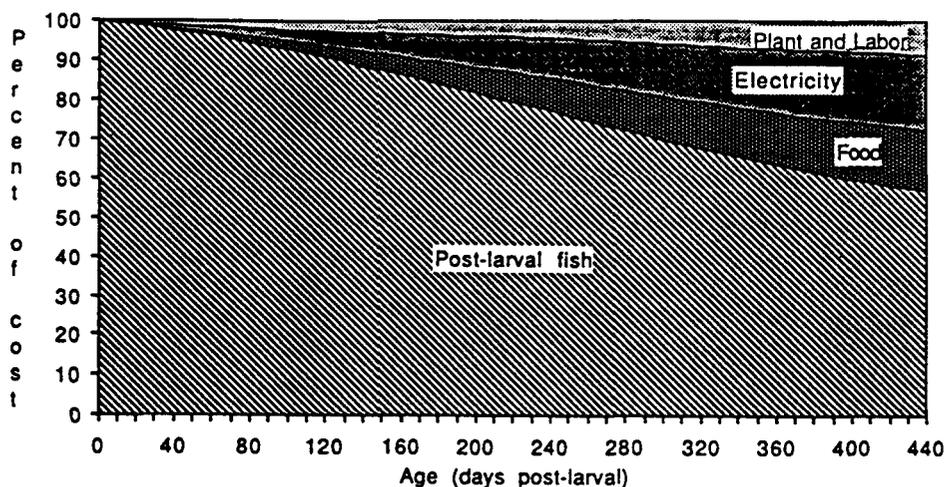


FIGURE 4. Distribution of costs per released fish by age at release as a proportion of total cost.

recruit, the cultured fish should be released after about 290 d of culture. The value of optimal release is sensitive to both the initial cost of post-larval fish and to the post-release survival rates.

*Graphical Analysis of Sensitivity*

Because of the preliminary nature of the research into culture of the post-larval fish, there is a great deal of uncertainty regarding the food characteristics and the culture units (tanks) necessary. Also, the growth rates observed in the culture system are lower than those observed in the wild population. We have therefore evaluated the sensitivity of culture-system performance to these parameter values. This is most easily done graphically.

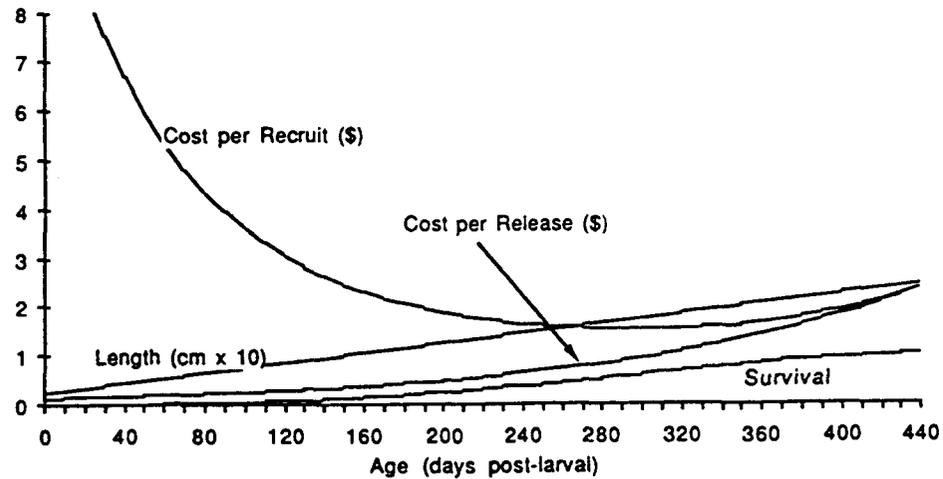


FIGURE 5. Cost per recruit (at 24 cm) if released from culture at the age on the horizontal axis. Other lines are the components of this cost (Equation 23).

Culture costs and operation of the culture system are sensitive to growth rate. We compare cost per recruit for six different values of growth rate in the culture plant (Figure 6). These lines are the same as the cost-per-recruit line in Figure 5 for different values of individual growth rate. Note that both the optimal time of release and the resulting cost per recruit are sensitive to this parameter. Little benefit would be gained by culturing the fish at growth rates less than 0.02 cm/d, and at rates as low as 0.01 cm/d continuing culture beyond the post-larval phase would increase the cost per recruit. Recall 0.025 cm/d is the highest observed laboratory growth rate and 0.05 cm/d is the estimated wild growth rate. This figure shows that for both of these values culture beyond the post-larval phase is optimal, but that the cost per recruit is high (e.g. for the former value, cost per recruit is near \$5.00).

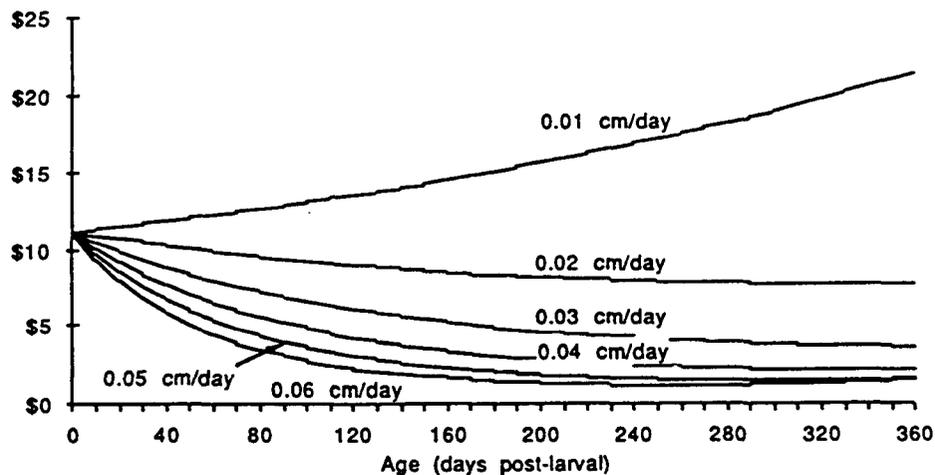


FIGURE 6. Cost per recruit as in Figure 5 for several different values of growth rate in culture.

Daily food costs and culture tank costs increase as the fish grow. Increases in the price of each of these has a significant affect on both the optimal release age and the cost per recruit (Figures 7 and 8). As food costs increase, cost per recruit increases, and the optimal release time decreases. The cost of tanks has a similar effect. Gadomski et al (1990) state that they have not been able to find a prepared food that post-larval halibut will utilize. Live food either collected or cultured is generally more expensive than prepared foods. Increased food costs would result in a younger optimum release age and a higher cost per recruit, but culturing beyond the post-larval phase is still cost effective in the sense that cost per recruit is less (but still expensive). A similar result occurs when cost per culture unit is varied.

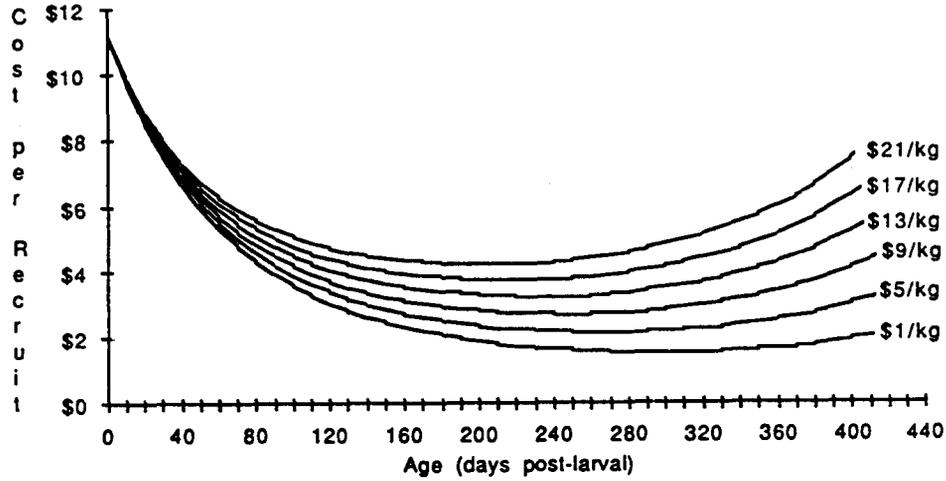


FIGURE 7. Cost per recruit for different food prices.

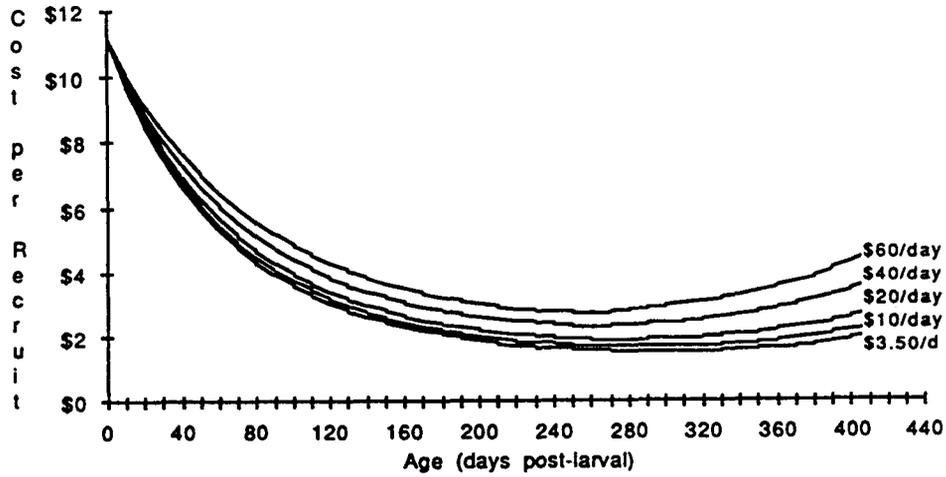


FIGURE 8. Cost per recruit for different costs of culture space.

Using increased food price as a typical increase in culture costs, we can examine the interaction of growth rate and culture costs (Figure 9). Even at high daily culture costs (food price of \$50.00/kg) the optimal release age is greater than zero when the growth rate is greater than 0.02 cm/d. Minimized cost per recruit when compared for the same values of growth rates and food prices indicates that at growth rates above 0.02 cm/d the minimized cost per recruit is sensitive to food price (Figure 10). For lower growth rates no further culture of postlarvae is warranted even at very low food prices, so minimized cost per recruit is the cost of stocking postlarvae. Expensive culture practices may be cost effective if they increase the growth rate significantly. For example, food that cost \$30.00/kg but increased the growth rate to 0.06 cm/d would result in a slight savings over \$1.00/kg food that resulted in a growth rate of 0.025 cm/d, and a food that cost \$10.00/kg with a potential growth rate over 0.04 cm/d would cut the minimized cost per recruit in half. Finally it should be noted that large increases in culture costs (e.g. 50-fold increase in food price) do not result in equivalent increases in minimized cost per recruit (approximately five fold), because a compensatory decrease occurs in optimal release age (Figures 9 and 10).

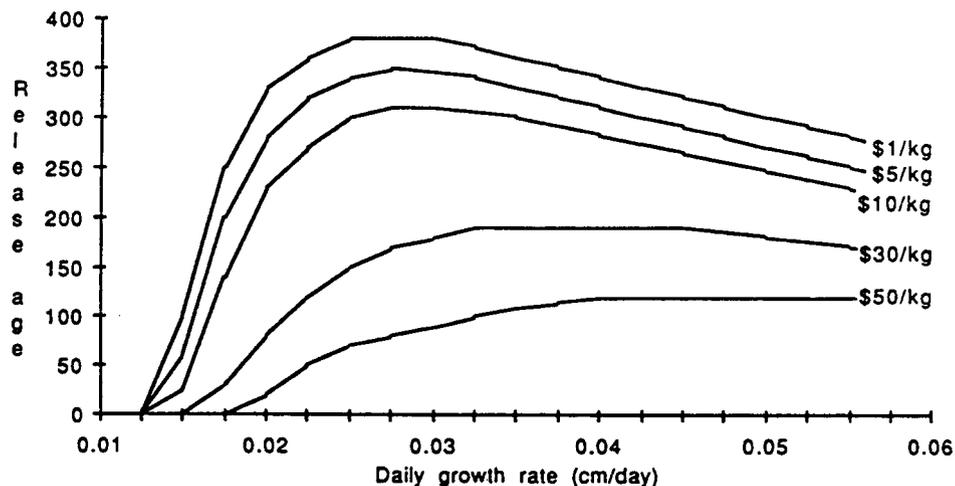


FIGURE 9. Optimal release age as both the cost of food and one of the potential effects of different foods, growth rate, vary.

Post-release mortality rates are also poorly known. In the model the post-release mortality parameter with the greatest uncertainty is the mortality of a post-larval fish (recall that post-release mortality rate is size dependent and decreases linearly from the post-larval size to recruit size, hence this is the value at lower end of this size range). Optimal release size, age, and cost, and the resulting cost per recruit, all increase with this parameter (Figure 11). The optimal values of these variables are those that correspond to the release age at which cost per recruit is minimized. The value of mortality rate used in the

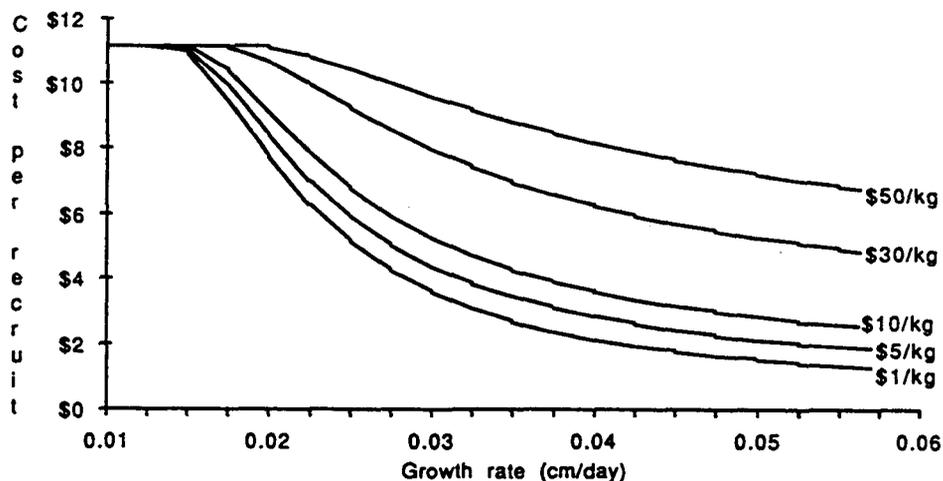


FIGURE 10. Cost per recruit (at 24 cm) as both the cost of food and growth rate vary.

baseline model is an instantaneous yearly rate of 7.0/year which would result in 1.3% survival from the post-larval size of 2.5 cm to the recruitment size of 24 cm. It is somewhat surprising to note that the cost per recruit varies relatively little (from \$1.30 to \$1.72) when the mortality rate is varied by a factor of two (from 5.0/year to 10.0/year or survival of 4.4% to 0.2% respectively). The cost per released fish varies by a factor of two (from \$0.64 to \$1.25), so the relative insensitivity of the cost-per-recruit variable results from an adjustment of the optimal release age (240 d to 340 d) that partly compensates for the variation in mortality rate.

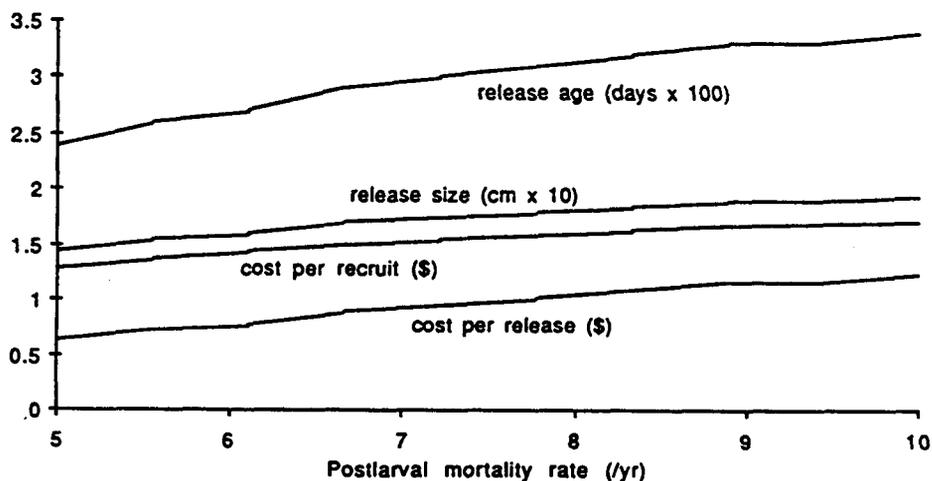


FIGURE 11. Optimal release age and size, and the associated cost per released fish and cost per recruit (at 24 cm) as the early natural mortality rate of juveniles is varied.

One question that would arise from Figure 11 is how sensitive cost per recruit is to changes in both parameters of the post-release mortality rate (i.e. both the post-larval value and the pre-recruit value). Even when both parameters are varied, one by a factor of two and the other by a factor of six, the cost per recruit varies only from \$1.19 to \$1.84 (Figure 12).

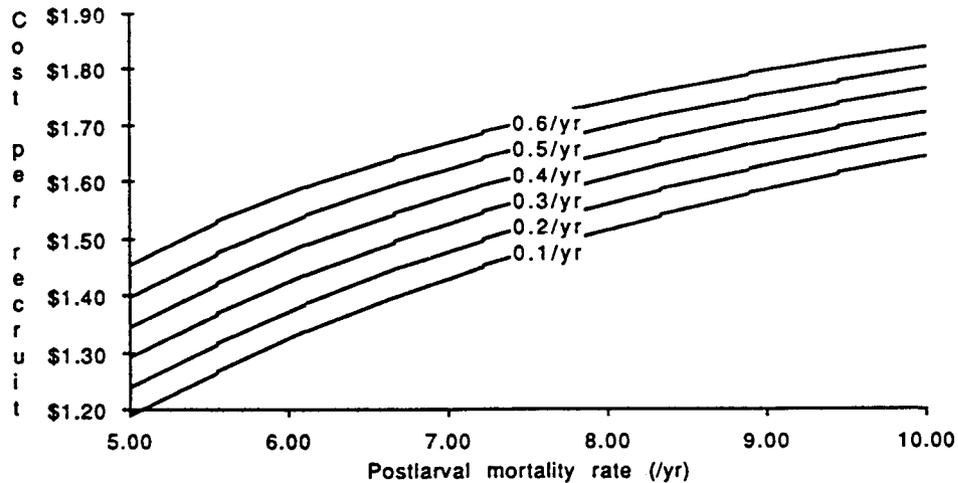


FIGURE 12. Cost per recruit as both the post-larval mortality rate (horizontal axis) and pre-recruitment mortality rate (individual lines) are varied.

### Post-Recruitment

Direct, short-term impacts of the stocking program are evaluated here in four different ways. Parameter values used are shown in Table 3. These results are presented for a range of lower size limits and fishing mortality rates so that both the sensitivity of results to poorly known fishing mortality rates and the possible effects of changes in fishery policy can be evaluated.

The fraction of recruited, stocked fish that ends up being caught increases with the amount of fishing (i.e. the fishing mortality rate) because fewer fish survive long enough to die from natural mortality (Figure 13). It also increases as the size limit is lowered because fewer fish die from natural causes before reaching legal size. To get an idea of what would result from current management, we can look at the current size limit of 55.9 cm and assume a total fishing mortality rate including both sport and commercial fishing of 0.25/year; the fraction caught would be 0.22. This depends critically on stocked fish having the same survival rate as that estimated for natural fish (see Table 3).

Biomass caught accounts for the fact that fish grow larger with age while the fraction caught declines. The catch in the fishery in terms of biomass per recruited, stocked fish is higher at higher fishing rates and at intermediate size limits (Figure 14). Near 55.9 cm and 0.25/year it is relatively flat, indicating that little would be gained by a change in fishery policy and that, even if our

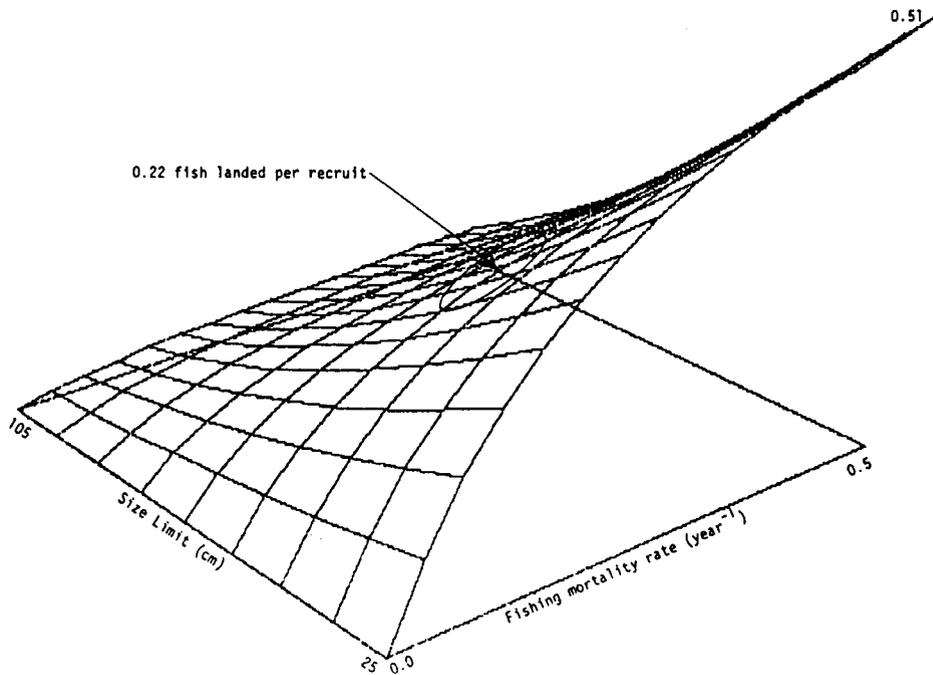


FIGURE 13. Fish landed per California halibut recruit as size limit and fishing mortality rate are varied. The area marked corresponds to the present fishery.

TABLE 3. Parameters and values for post-recruitment model for California halibut

Symbol	Parameter	Value
m	Natural mortality rate	0.20/yr
a <sub>1</sub>	Coefficient of length to weight (cm to kg) function	0.872 X 10 <sup>-5</sup> kg
b <sub>1</sub>	Exponent for length to weight (cm to g) function	3.048
a <sub>2</sub>	Maximum length (for Von Bertalanffy length at age)	128.5 cm
b <sub>2</sub>	Growth parameter (for Von Bertalanffy length at age)	0.1207/yr
c <sub>2</sub>	Age at length zero (for Von Bertalanffy length at age)	0.0983 yrs
P <sub>r</sub>	Culture cost per recruit	\$1.13/recruit
p <sub>k</sub>	Value per kilogram of fish caught in fishery	\$4.00/kg

estimates of fishing mortality rate are off a bit, our projected biomass yield will not be far off. The value at that point is approximately 0.93 kg.

The two criteria evaluated thus far do not include the costs of stocking. The cost per stocked fish caught for California halibut is shown for various values of fishing rate and size limit in Figure 15. For low fishing rates and high size limits, this criterion is high (because few fish are caught). However, near the current operating point the cost is about \$5.05 for a landed fish that would average 4.2 kg (yield per recruit / fraction caught). This cost could be reduced by lowering the size limit, but that would lead to smaller fish in the catch.

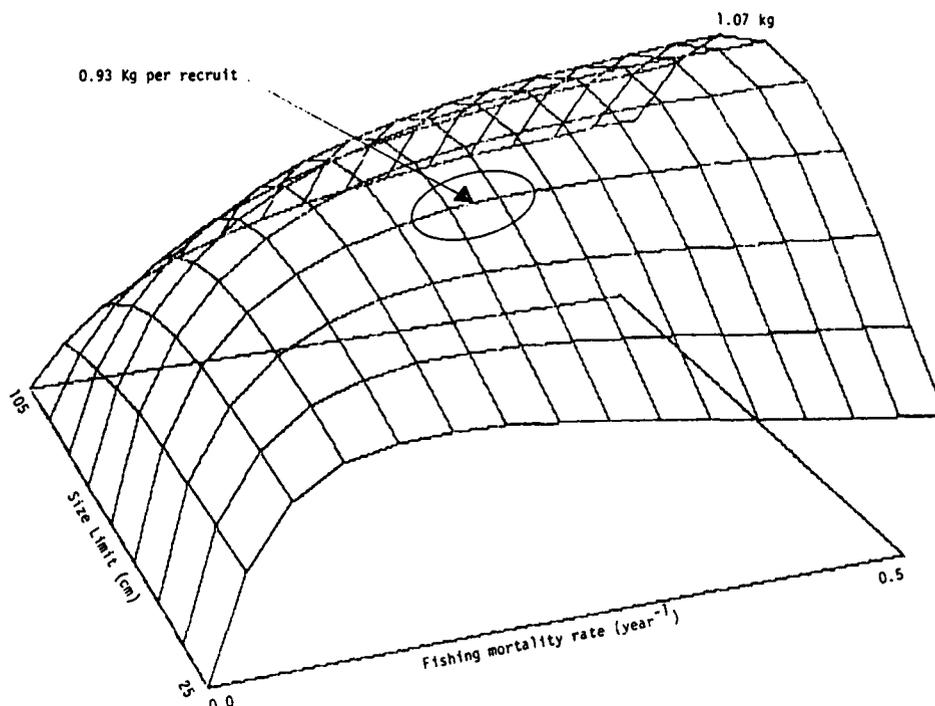


FIGURE 14. Biomass yield per California halibut recruit as size limit and fishing mortality rate are varied. The area marked corresponds to the present fishery.

A way of including the size of the fish in an economic criterion is to compute the difference between value to the fisherman (assuming it is proportional to weight) and the cost of culturing the fish. Net benefit is shown in Figure 16 for a value of \$4.00/kg. This increases with fishing rate then decreases slightly and is a maximum for intermediate size limits. At the current operating point the net benefit is about \$2.84 per recruit. The curve is fairly flat in the vicinity of this point.

A characteristic common to all of the four criteria is that they are sensitive to the assumed value of natural mortality rate. As one moves from a low estimate of 0.1/year to a high estimate of 0.3/year, biomass yield per recruit declines from 2.40 kg to about 0.43 kg (Figure 17) and the cost per stocked recruit caught increases from \$2.50 to about \$10.00 (Figure 18).

### CONCLUSIONS FROM ANALYSES TO DATE

The analyses, thus far, raise some important issues that are worthy of attention. With regard to the culture phase, the fact that the cost of post-larval fish may dominate costs is important. For the analyses described here, we used a price (\$0.15) which is less than the cost of commercially produced postlarvae of striped bass, *Morone saxatilis*, (for which females are also captured, and

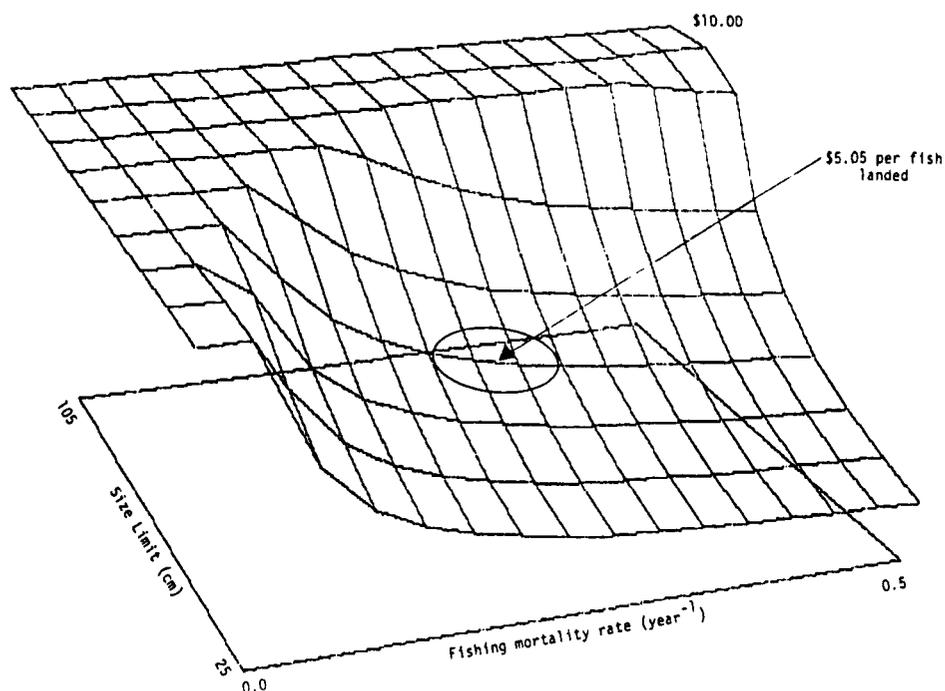


FIGURE 15. Average cost per stocked California halibut recruit as size limit and fishing mortality rate are varied. The area marked corresponds to the present fishery.

postlarvae are also reared from eggs). Using this value, costs of postlarvae are a major part of culture costs. This would imply that more attention should be paid to reducing this cost. Also, an accurate estimate of these costs is necessary because of its effect on the decision regarding optimal time of release.

A graph such as Figure 5 is the best single summary of how the culture/stocking scheme works. The variation in cost per recruit as time of release from culture increases, indicates the optimal time of release, as well as the penalty for early or late release. It is somewhat surprising that cost per recruit is relatively insensitive to post-release mortality (Figure 11, 12). However, this result assumes that we know the post-release mortality rates, and can release the cultured fish at the optimal release time. It will be advisable to monitor survival during the post-release/pre-recruit period, and to continue to refine optimal release time, even after the project begins releasing cultured fish.

Figure 5 can be used to evaluate some of the recent conclusions by the halibut culture researchers. For example, the annual progress report for 1987–88 for California halibut (Stephens et al. 1988) stated that the best release age was 6 to 7 weeks, primarily because of lack of an available food and space limitations in culturing a bottom dwelling fish. However, modeling results described here indicate the cost per recruit at this age would be about \$6.00 per fish (Figure 5). Thus, it appears that release at this age is not economically feasible, and that further research is required to develop the capability of

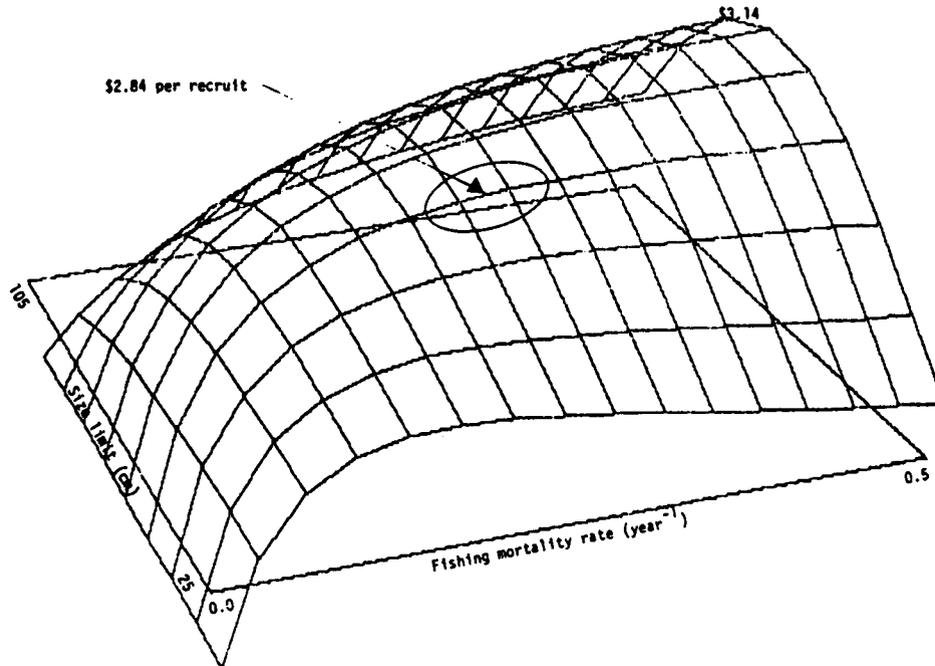


FIGURE 16. Net benefit per stocked California halibut recruit as size limit and fishing mortality rate are varied. The area marked corresponds to the present fishery.

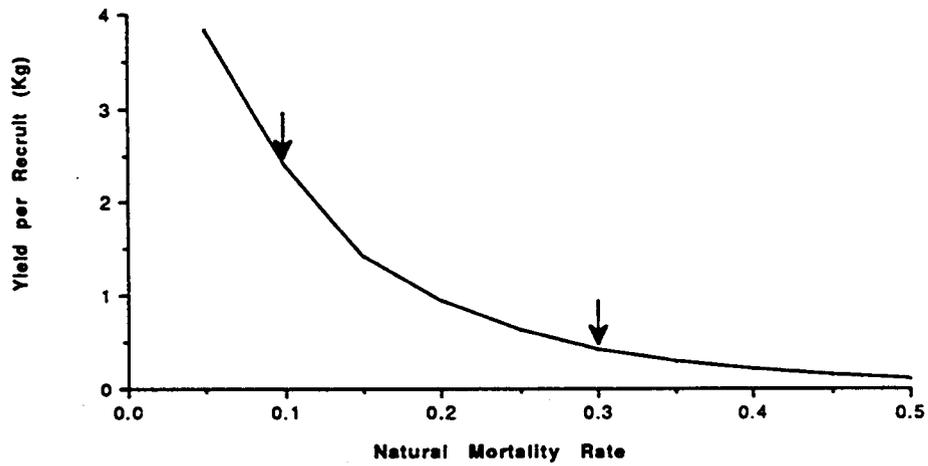


FIGURE 17. Biomass yield per California halibut recruit as natural mortality rate is varied. Arrows indicate recent low and high estimates of natural mortality rates.

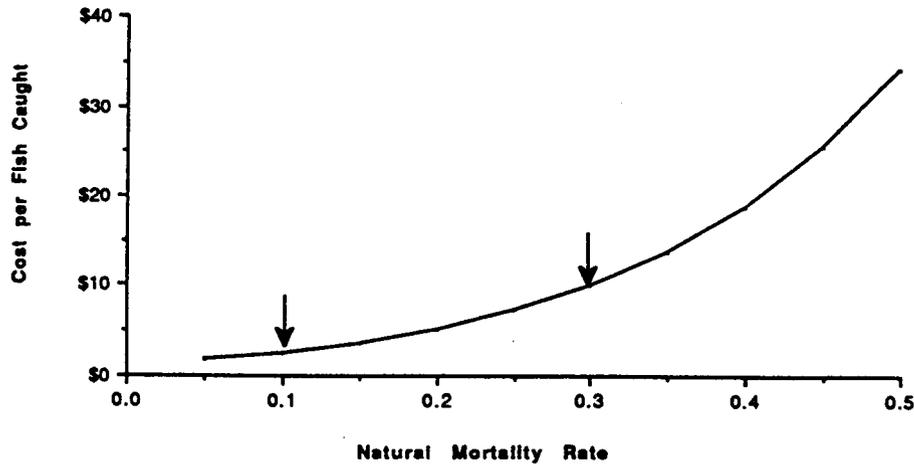


FIGURE 18. Average cost per stocked California halibut recruit caught in the fishery as natural mortality rate is varied. Arrows indicate recent low and high estimates of natural mortality rates.

culturing these fish to older ages. The economic analysis indicates that costs for food and culture space can be much higher than our baseline estimates and still result in substantial savings with culturing to an older release age (Figures 7 and 8). Other flatfish species have been cultured to larger sizes (Bardach et al. 1972).

Figure 6 reflects the implications of the current halibut growth rate. If growth rates are less than 0.02 cm/d, culture is not optimal (i.e. the optimal age of release is zero). If the growth rate is about 0.025 cm/d, the cost per recruit is about \$8.00. A growth rate approximating the wild growth rate (0.05 cm/d) is required to bring the cost per recruit down to about \$1.50.

The post-recruitment analysis provides an understanding of the economics of the culture/stocking system in terms of the fishery. We do not yet have the data necessary to confidently estimate culture costs, but the results illuminate sensitivity to various parameters. For example, they emphasize the importance of natural mortality rates. All criterion were sensitive to the value of that parameter. For California halibut the value probably lies between 0.1/year and 0.3/year, but this limited range allows a large uncertainty in the feasibility analysis. Because of the difficulty in estimating mortality rates in natural populations (Vetter 1988), some uncertainty will always be present in evaluations of the feasibility of the culture/stocking scheme.

Implications of current model results for feasibility of the culture/stocking concept are not straightforward. Cost and benefit projections appear high (about \$5 per fish caught and a net benefit of \$3 per fish if their value is \$4/kg). However, these are based on growth at a rate near the natural rate to optimal release size. This growth rate is greater than current rates in culture and the optimal release size is far beyond the size to which researchers have thus far been able to grow this fish. If released at that size, cost per fish caught would be about \$18, a value that is probably too high.

Overall evaluation of feasibility would also include consideration of less tangible effects of culture that are not included in our analysis. One example is the contribution of cultured fish to future recruitment. This would presumably be positive; however, there might be negative effects on genetic variability. Another less tangible effect is the negative effect that culture might have on the ability to protect habitat in the future. Some might assume that because fish could be cultured, there was less reason to protect natural spawning habitat.

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## APPENDIX A

Variable	Description
$L_t$	length at time t
$W_t$	weight at time t
$\delta_w$	$W_{t+1} - W_t =$ weight gain per fish per time step
$N_t$	number of fish at time t
$F_t$	weight of food required per fish per time step
$O_{2t}$	oxygen requirement per fish at time t
$NH_{3t}$	ammonia produced in time step t
$H_2O_t$	total water required per fish in time step t
$O_{2d}$	deficit in grams of dissolved oxygen per fish
$T_t$	number of tanks required at time t Cft cost for food in time step t
$C_{et}$	cost for electricity in time step t CH <sub>2</sub> O <sub>t</sub> cost for inflow water in time step t
$C_{At}$	total cost to culture to age t
$t_L$	time from stocking to recruitment
$m_L$	average mortality rate for fish from release to recruitment
$S_L$	average survival rate for fish from release to recruitment
$C_{rt}$	cost per fish stocked at time t that reaches recruitment
$S_t$	portion surviving from recruitment
$C_r$	catch per recruit, the fraction of recruited, stocked fish caught
$Y_r$	yield per recruit
$P_f$	culture cost per fish caught
$B_r$	net benefit = value of yield per recruit - cost per recruit

## APPENDIX B

The computer programs used in both the cost estimates and the sensitivity analysis have been developed for distribution and can be obtained by writing the authors. The programs are written in TURBO Pascal to run on IBM-compatible personal computers. The programs make use of a graphics package that is specific to the graphics system on the computer. Information on the graphics environment, in which the programs will be run, should be included with the request.