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Abstract

A simple bioeconomic model was specified and estimated for the central subpopulation of the northern anchovy (*Engraulis mordax*). Net population growth was described by a power function and harvest by the U. S. reduction fleet was modelled by an exponential production function. When incorporated into a bioeconomic model they allowed the derivation of two explicit functions, $Y = \phi(X)$ and $Y = \psi(X)$ which could be used to depict the bioeconomic optimum. The roots of $\phi(X)$ have important economic interpretations and can be used to characterize the economic status of the fishery. The positively-sloped segment of the $\phi(X)$ curve may be used as an approximately-optimal adaptive management policy.

For the set of bioeconomic parameters *circa* 1990, anchovy biomass would need to increase to about 1 million metric tons before arousing the economic interest of the wetfish fleet. Alternatively, a price/cost ratio of 0.6 or more would imply positive net revenues at a biomass of 350,000 metric tons. The current price/cost ratio may be as low as 0.1 and the current estimate of biomass is about 300,000 metric tons. Thus, unless there is a dramatic increase in the demand for oil and fish meal or a spectacular increase in biomass, it seems unlikely that there will be a resurgence in the reduction fishery for anchovy in the near future.

Keywords: bioeconomics, northern anchovy

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I. Introduction

The northern anchovy (*Engraulis mordax*) is a small schooling fish found in three subpopulations that range from the southern tip of Baja California, Mexico to Queen Charlotte Sound off the coast of British Columbia (see Figure 1). This paper is concerned with the bioeconomics of the central subpopulation which is harvested by both Mexican and U. S. vessels.

Historically, most of the catch was "reduced" (or processed) into oil and fish meal and sold as a protein supplement for use in poultry feed. About 3,000 - 6,000 metric tons (mt) per year are harvested live for use as bait in various sport fisheries, while another 1,000 - 3,000 mt per year are harvested for other commercial products, such as pet food. During its peak years in the mid-1970s the reduction fishery accounted for about 90 percent of the total U. S. harvest. In the 1980s, landings for reduction declined below 6,000 mt annually and were exceeded by nonreduction landings for most of the decade.

The fleet of U. S. reduction vessels is based in California and is comprised of small purse seiners averaging 20 meters in length

(Thomson *et al.* 1990). Most of these vessels are from the San Pedro fleet, operating from docks in the Los Angeles harbor. Port Hueneme, near Santa Barbara, is the next largest port and a few vessels work out of Monterey.

About one-third of the fleet is steel hulled, having been built within the last 25 years, while the rest of the vessels are wooden hulled and date back the heyday of the Pacific sardine fishery in the 1930s and 1940s. This fleet is collectively referred to as the "wetfish fleet" because anchovy and the other species traditionally taken by these vessels were packed whole (and thus "wet"). The fleet continues to harvest Pacific mackerel, jack mackerel, Pacific bonito, Pacific sardine, market squid, bluefin and other tunas. Pacific mackerel has been the mainstay of the fleet during much of the 1980s.

The composition of landings is influenced by species abundance *and* exvessel (dockside) prices. In recent years the wetfish fleet has had little economic incentive to harvest anchovy, due to relatively low exvessel prices and low abundance. Table 1 reveals an average price of $32 per metric ton over the last four years (1987-1990). This compares with $150 - $200/mt for mackerel and sardine, $175 - $275/mt for squid, $200 - $450/mt for bonito and $1,000 - $5,000/mt for tuna (Jacobson and Thomson 1991).

The central subpopulation is managed by the Pacific Fishery Management Council (PFMC) which sets an annual quota for the reduction fishery. From 1983 until 1990 the quota was determined using the following formula. Let SB_t denote the estimate of spawning biomass at the beginning of year t. Then the quota, Q_t, in metric tons, was calculated as $Q_t = (SB_t - 300{,}000 \text{ mt})$ if $SB_t > 300{,}000$ mt (up to a maximum Q_t of 200,000 mt), or $Q_t = 0$ if $SB_t \leq 300{,}000$ mt.

During the 1980s the quota for the reduction fleet was never binding. In 1990, when spawning biomass fell below 300,000 mt, an emergency reduction quota of 5,000 mt was granted by the Department of Commerce.

There is no quota for the live bait fishery. Other nonreduction harvest (such as pet food) is limited to 7,000 mt unless spawning biomass falls below 50,000 mt for two years in a row.

It is somewhat ironic that the low exvessel price for anchovy has made management easier or at least less controversial. Table 2 provides recent estimates of total biomass and total harvest (by U. S. and Mexican vessels). The biomass estimates are from Jacobson and Lo (1991) and were derived using a stock synthesis model (SSM), which is a large age-structured simulation model where 33 parameters

are estimated by maximizing a composite likelihood function based on fishery *and* fishery-independent data [see Methot (1989) for details]. The 1990 biomass estimate is 299,410, the lowest its been since 1964. If the exvessel price were high, and vessels of the wetfish fleet were keen to harvest anchovy, pressure to increase the quota would be considerably greater.

The objective of this paper is to construct a simple bioeconomic model that will shed light on the combination of price, cost and biomass for which the anchovy fishery would be profitable. Jacobson and Thomson (1991) have examined the implied wage to crew members for alternative prices, biomass levels and fuel costs. Their model is static, and while helpful in indicating the combinations of price, fuel cost and biomass which might provide a competitive wage, it does not explicitly incorporate the opportunity cost of capital (via a discount rate) and cannot determine the long-run levels for biomass, harvest and profit if the fishery were managed to maximize present value.

The remainder of this paper is organized as follows. In the next section we specify and estimate a simple model of population dynamics. In the third section a fishery production function is estimated where harvest is a function of seasonal biomass and hours

fished. The two components are combined in a bioeconomic model in Section IV, and the long-run bioeconomic optimum is identified for a range of exvessel prices, hourly cost and rates of discount. The final section discusses the results and offers some tentative conclusions.

II. Population Dynamics

We begin by defining the notation and units of measurement which will be used throughout the rest of the paper. Let

X_t = the biomass (mt) of anchovy in year t,

Y_t = the total harvest (mt) of anchovy in year t,

H_j = the harvest (mt) by the U. S. reduction fleet in season j,

E_j = the effort (hours fished) in season j,

B_j = the average biomass (mt) in season j,

q = a positive production parameter (1/hours),

p = the exvessel price of anchovy ($/mt),

c = the cost per unit effort ($/hour),

δ = the real, inflation-free, annual rate of discount,

$\rho = 1/(1 + \delta)$ = the *financial* discount factor in year t,

d = the *biological* discount factor in year t,

C_t = the total cost of harvesting anchovy in year t ($/year),

π_t = the net revenue from harvesting anchovy in year t ($/year).

The dynamics of the northern anchovy has been studied by both biologists and economists. Models have ranged from simple biomass models, such as those by Radovich and MacCall (1979), Huppert et al. (1980) and MacCall et al. (1983), to the age-structured, SSM of Methot (1989). Because of the difficulty of optimization with an age-structured model, a simple biomass model was adopted. The dynamics of the anchovy population are assumed to follow a first-order difference equation taking the general form

$$X_{t+1} = F(X_t)\, e^{\varepsilon_t} - dY_t \tag{1}$$

where ε_t is a normally distributed error term with zero mean and d is referred to as the *biological discount factor* by MacCall (1978). There are two possible effects that might give rise to the biological discount factor. First, the reduction in future biomass from harvest is overstated because some of the fish which were harvested would have died of natural causes. Second, biomass not harvested might suppress the growth of those that survive due to intraspecific competition for available food. On the basis of recent research, L. D. Jacobson (personal communication 7/15/91) suggests that $d \approx 0.75$.

Several possible forms for $F(X_t)$ were fit to the biomass and harvest data in Table 2. The best fit was obtained by the power function $F(X_t) = aX_t^b$, where one would expect $a > 1$ and $1 > b > 0$. The estimated model takes the form

$$\ln [X_{t+1} + dY_t] = \ln a + b \ln X_t + \varepsilon_t \qquad (2)$$

where ln is the natural log operator.

The OLS results, after correcting for first-order autocorrelation, are given in Table 4. The very high R^2 and significant coefficients suggests that the simple difference equation should closely track the SSM model. This is verified in Figure 2 where the SSM biomass and the predictions from the OLS regression are plotted.

A much more difficult test of the model is to simulate the biomass from an initial condition and then compare the results to the biomass estimates from the SSM. The parameter "a" is adjusted by an approximation suggested by Beauchamp and Olson (1973), and is set equal to $a = e^{\ln a + s^2/2} = 5.111$. With $b = 0.888$ and $d = 0.75$, Figure 2 also shows the simulation from $X_0 = 650{,}842$. It reveals a steady increase in biomass until 1974, then a steady decline until 1985 when there is a slight increase to 318,865 mt, followed by a decline to

263,808 mt in 1989 before increasing to 269,463 mt in 1990. Overall, the simple difference-equation model results in stock dynamics that are consistent with the prevailing opinion on the history and current status of the central subpopulation of anchovy.

The concept of maximum sustainable yield (MSY) is no longer regarded as an appropriate management objective in a stochastic environment. If it is maintained for any length of time it can result in depletion of a fish stock. Beddington and May (1977) conclude that a feedback control policy should be adopted when managing a renewable resource subject to stochastic recruitment. The MSY value presented here is offered only as a means of comparing the present model with previous models of the central subpopulation of northern anchovy.

The steady-state expected yield for the power function becomes

$$Y = \psi(X) = (aX^b - X)/d \tag{3}$$

The stock supporting maximum sustainable yield is given by

$$X_{MSY} = \left(\frac{1}{ab}\right)^{1/(b-1)} \tag{4}$$

For a = 5.111 and b = 0.888 one obtains X_{MSY} = 733,410 mt with MSY = 123,336 mt. Radovich and MacCall (1979) estimate X_{MSY} = 1,814,388 mt and MSY = 408,237 mt. Huppert (1981) estimates MSY to be 471,741 mt. Thus, in comparison with biomass models estimated during the high-yield 1970s, the current parameter estimates of the power-function imply considerably lower expectations as to maximum sustainable yield.

III. Production

Table 3 contains estimates of harvest (H_j) by the U. S. reduction fleet, hours fished (E_j) and average biomass (B_j) for the seasons 1965/66 through 1989/90. These data were used to estimate a fishery production function of the form

$$H_j = B_j \left(1 - e^{-q E_j + \mu_j}\right) \tag{5}$$

where j is an index for season and μ_j is a normally distributed error term with zero mean. The estimated form is

$$\ln \left[(B_j - H_j)/B_j\right] = \alpha - q E_j + \mu_j \tag{6}$$

where it is expected that α would *not* be significantly different from zero and that q would be significantly positive.

The results of the OLS regression, corrected for second-order autocorrelation are also contained in Table 4. The adjusted R^2 is 0.9081 and the coefficients α and q are of the expected sign and significance. The production parameter q = 9.558 E -6 takes its place alongside a = 5.111, b = 0.888 and d = 0.75 in our base-case parameter set. To complete the set of bioeconomic parameters we need estimates of the exvessel price, p, the hourly cost of vessel operation, c, and the discount rate, δ.

IV. Bioeconomics

A common economic objective for the management of a fishery facing competitive output and factor markets, and without significant sport fishing harvest, is the maximization of discounted net revenue. If the anchovy population were to recover to biomass levels of the mid-1970s and if the *non*reduction harvests remain in the range of 5,000 to 7,000 mt annually, the maximization of discounted revenue would seem a reasonable objective for fisheries management. The same concerns expressed by Beddington and May (1977) over MSY might

also be levied against the slavish pursuit of a single bioeconomic optimum. In this section we will derive expressions for optimal biomass, yield and effort as a function of the full set of bioeconomic parameters. We will then conduct sensitivity analysis on cost, price and the discount rate. An approximately-optimal adaptive management policy is also identified.

To begin, we derive a *cost function* based on a cost equation and the production function, recast on an annual basis. Specifically, we assume that annual operating costs may be calculated as $C_t = cE_t$ and that reduction harvest on an annual basis can be represented by the production function $Y_t = X_t(1 - e^{-qE_t})$ where the estimate of q from the seasonal data is assumed appropriate for an annual model as well. By solving the production function for E_t as a function of X_t and Y_t and substituting into the cost equation one obtains the cost function

$$C_t = (c/q)\ln [X_t/(X_t - Y_t)] \tag{7}$$

and net revenue may be calculated as

$$\pi_t = pY_t - (c/q)\ln [X_t/(X_t - Y_t)] \tag{8}$$

The maximization of discounted net revenues may be mathematically stated as

$$\text{Maximize} \quad \sum_{t=0}^{\infty} \rho^t \{pY_t - (c/q)\ln [X_t/(X_t - Y_t)]\}$$

$$\text{Subject to} \quad X_{t+1} = aX_t^b - dY_t$$

Associated with this problem is the current-value Hamiltonian

$$\bar{H}_t = pY_t - (c/q)\ln [X_t/(X_t - Y_t)] + \rho\lambda_{t+1}[aX_t^b - dY_t - X_t] \tag{9}$$

where λ_t is the current-value costate variable, reflecting the marginal value of an additional metric ton of anchovy, in the water, in year t.

The first-order necessary conditions include

$$\frac{\partial \bar{H}_t}{\partial Y_t} = \frac{pq(X_t - Y_t) - c}{q(X_t - Y_t)} - d\rho\lambda_{t+1} = 0 \tag{10}$$

$$\rho\lambda_{t+1} - \lambda_t = -\frac{\partial \bar{H}_t}{\partial X_t} = -\frac{cY_t}{qX_t(X_t - Y_t)} - \rho\lambda_{t+1}[abX_t^{b-1} - 1] \tag{11}$$

$$X_{t+1} - X_t = \frac{\partial \tilde{H}_t}{\partial[\rho\lambda_{t+1}]} = aX_t^b - dY_t - X_t \tag{12}$$

Equations (10)-(12) must hold along an approach path and in equilibrium. In steady state equations (10) and (11) imply

$$Y = \phi(X) = \frac{[(1+\delta) - abX^{b-1}][pqX - c]X}{\{[(1+\delta) - abX^{b-1}]pqX + cd\}} \tag{13}$$

When equation (12) is evaluated in steady state we obtain the equilibrium relationship between harvest and yield previously listed as equation (3); that is, $Y = \psi(X) = [aX^b - X]/d$. The intersection of $\phi(X)$ and $\psi(X)$ defines the steady-state bioeconomic optimum, (X^*, Y^*). Because $\phi(X)$ and $\psi(X)$ are nonlinear functions, there is a possibility of more than one intersection.

Figure 3 shows a graph of $\phi(X)$ and $\psi(X)$ for the case where

$$X_1 = \left[\frac{(1+\delta)}{ab}\right]^{1/(b-1)} < X_2 = \frac{c}{pq} \tag{14}$$

Mathematically, X_1 and X_2 are roots of $\phi(X)$. They have, however,

interesting and important economic interpretations. X_1 would define optimal biomass in a model where cost did *not* depend on the size of the fish stock. Specifically, if equation (3) is substituted into equation (13) we obtain a single equation in X that may be written

$$(abX^{b-1} - 1) + \frac{cd(aX^{b-1} - 1)}{pq[(1+d)X - aX^{b}] - cd} = \delta \qquad (15)$$

Equation (15) is a special case of the "fundamental equation of renewable resources" [see Conrad and Clark (1987)] On the left-hand-side (LHS) of equation (15) are two terms. The first term is the derivative of the power function minus one and represents the marginal rate of growth in anchovy biomass. The second, more complex term, is called the "marginal stock effect" (MSE), and measures the marginal value of an additional unit of biomass in reducing harvest cost [see Clark and Munro (1975)]. Taken together, these two terms define what has been called "the resource's internal rate of return." Optimal biomass, from a bioeconomic perspective, is that value of X which equates the resources internal rate of return to the financial rate of discount, δ.

If the marginal stock effect were zero, and there were no cost savings associated with larger biomass, then the optimal stock would

be $X_1 = [(1 + \delta)/(ab)]^{1/(b-1)}$. This is *not* the case in our present model. Analysis of the cost function given in equation (7) will reveal that an increase in X_t, for Y_t constant, will *lower* cost. If $\delta = 0$, $X_1 = X_{MSY}$ [refer to equation (4)]. When $\delta > 0$ and $1 > b > 0$, $X_1 < X_{MSY}$.

The second intercept in Figure 3 is $X_2 = c/(pq)$. This is familiar to resource economists as the equilibrium stock in the Gordon-Schaefer model under *open access* [see Clark (1990)]. In that model $c/(pq)$ was a "breakeven" biomass. If $X > c/(pq)$, net revenue was positive and effort would expand, whereas if $X < c/(pq)$ net revenue would be negative and effort would contract. The intercept X_2 can be thought of as the "minimum-viable economic biomass" for a profit-seeking industry.

The specific implications of the intercepts X_1 and X_2 for the management and economic value of the central subpopulation of anchovy might be summarized as follows.

1. In the present model, where an increase in biomass *will* reduce cost, the optimal biomass, from the manager's perspective, *must always* lie above X_1 which is the optimal biomass when the MSE = 0.

2. There are plausible values for [a,b,δ] and [c,p,q] that will result in $X_1 < X_2$, as in Figure 3, or $X_1 > X_2$. When the exvessel price is low relative to cost, it is likely that $X_1 < X_2$. This seems to characterize the current situation in the anchovy fishery.

3. If $X_1 > X_2$, $\phi(X)$ will have the *same shape*. The extent to which X^* lies above X_1 will depend on the size of the cost savings inherent in higher levels of biomass.

4. The intercept X_2 is a critical value *from the industry's perspective*. The industry would not be interested in fishing a biomass less than X_2 because net revenue would be negative. If $X_1 < X_2$ managers, as noted earlier, will not be under much pressure to increase the quota.

5. The positively-sloped segment rising from the right-most intercept may be used as an approximately-optimal feedback control as recommended by Beddington and May (1977). (This is discussed in greater detail below).

What are plausible values for c, p and δ? We saw from Table 1 that the average exvessel price over the last four years was \$32/mt. It is more difficult to pin down the hourly operating cost of a purse seiner in the wetfish fleet. Jacobson and Thomson (1989) assume a point estimate of \$288.29/hr. In more recent analysis, L. D. Jacobson (personal communication 7/23/91) suggests that hourly operating costs might range from \$100 to \$300/hour.

Table 5 shows the results of varying price, cost and the discount rate. There are 27 cases, corresponding to three prices, \$30, \$60 and \$90/mt., three discount rates, 0.02, 0.04 and 0.06 and three estimates of hourly operating costs, \$100, \$200 and \$300/hr. The values of a = 5.111, b = 0.888, d = 0.75 and q = 9.558 E -6 are the

same for all cases. It seems likely that the combinations of c, p and δ will cover not only the current situation but also the near-term future.

In each "cell" in Table 5 we list the optimal biomass, X^*, harvest, Y^*, hours fished, E^*, industry net revenue, π^*, and the intercepts X_1 and X_2. Consider the situation when p = \$30/mt, c = \$300/hour and $\delta = 0.04$. The optimal biomass is $X^* = 1{,}488{,}756$ mt supporting a yield of $Y^* = 79{,}953$ mt from a fleet fishing 5,775 hours. Annual net revenue for the industry would be \$516,729. In this case $X_1 < X_2$ and presumably the industry would have no interest in fishing until the stock reached a biomass of $X_2 = 1{,}046{,}244$. This case may be close to the bioeconomic reality currently facing the industry. The fact that some fishing for reduction took place in 1990 might be explained by a vessel receiving a single contract to provide a limited amount of anchovy at an above market price. Alternatively, the one vessel that participated in the fishery in 1990 might have been exploring to see if a profitable biomass existed at the current price/cost ratio. Upon learning that it didn't, that vessel probably shifted to Pacific mackerel or bonito.

Careful inspection of Table 5 will reveal the following properties about the bioeconomic model. First, X^*, Y^*, and E^* depend on δ and the price/cost ratio. In other words, if δ and p/c are the

same, optimal biomass, harvest and effort will be the same. Net revenue, however, will depend on the absolute values of p and c.

The cases in Table 5 cover situations where p/c ranges from 0.1 to 0.9. Higher price/cost ratios lead to lower levels for optimal biomass and higher levels of effort. If X^* is reduced but remains to the right of X_{MSY}, harvest will *increase*. This is observed when moving down a column in Table 5; allowing p to increase for c constant.

As the discount rate increases (moving across a row in Table 5), optimal biomass declines, effort increases and harvest will increase if the new intersection of $\psi(X)$ and $\phi(X)$ remains to the right of X_{MSY}. This is a standard result in most bioeconomic models.

There are only three cases in Table 5 where the optimal biomass is less than X_{MSY}. These occur at p = \$60/mt, c = \$100/hr and $\delta = 0.06$ (X^* = 706,503 mt) and when p = \$90/mt, c = \$100/hr and $\delta = 0.04$ (X^* = 694,871 mt) and $\delta = 0.06$ (X^* = 631,012 mt). In each of these cases $X_2 < X_1$ and the wetfish fleet, when faced with such an attractive price/cost ratio, would probably desire a larger quota, pushing to reduce biomass toward X_2.

What about adaptive management on a year-to-year basis? This might be accomplished by using the positively-sloped segment, rising

from the right-most intercept, as an approximately-optimal feedback control. First, note that the positive intercept of the $\psi(X)$ curve occurs at $X_{MAX} = (1/a)^{1/(b-1)}$. Then depending on the updated or expected parameter set [a,b,c,d,δ,p,q] it is possible to calculate which intercept is largest. For example, if one expected that p = \$60/mt, c = \$100/hr and δ = 0.04, X_1 = 516,729 mt is the right-most intercept. For a = 5.111 and b = 0.888, X_{MAX} = 2.118 E 6, and 516,729 mt to 2,118,000 mt would be the range for adaptive management.

Suppose biologists anticipate a biomass of 550,000 mt. Substituting this value into $\phi(X)$ [see equation (13)] one would obtain a "recommended economic catch" (REC) of 11,103 mt. Alternatively, if the estimate were 700,000 mt, the above parameter set would result in a REC = 82,462 mt. If the estimate of current biomass were below X_1, the recommended economic catch is zero. Thus, the right-most intercept assumes the role of the "razor's edge" which is fixed at 300,000 mt under current PFMC policy.

The use of curves such as $\phi(X)$ as an approximately-optimal feedback control was first suggested by Burt (1964) and has been examined in greater detail by Burt and Cummings (1977) and Kolberg (1991). Conrad (1991) uses a similar approach in deriving an adaptive management rule for the Pacific whiting.

V. Conclusions

In retrospect, this paper has hopefully accomplished two objectives. The first was to demonstrate how to construct, estimate and analyze a simple bioeconomic model. The second was to learn something about the current status and likely future of the reduction fishery for anchovy from the central subpopulation.

The data for estimating growth and production functions was presented in Tables 2 and 3. The data gave strong support for the power function as a description of net biological growth. An exponential production function fit the seasonal data on harvest, hours fished and biomass. These two forms combined to produce a tractable bioeconomic model; that is, a model that required only seven bioeconomic parameters and which produced equilibrium relationships [$\phi(X)$ and $\psi(X)$] that allowed the depiction and numerical analysis of the long-run bioeconomic optimum. In the spirit of Beddington and May (1977), the relationship $Y = \phi(X)$ could be used for adaptive management when updating bioeconomic parameters and estimates of current biomass.

What was learned about the anchovy fishery? The numerical analysis in Table 5 identified the magnitude of the change in price,

cost or biomass which will be needed to make the fishery economically viable. In particular, if the cost of operating a wetfish purse seiner is about $300/hr, and if price remains at about $30/mt, the industry is unlikely to have any interest in anchovy unless the biomass increases to over 1 million metric tons. At a price of $60/mt and a cost of $200/hr the optimal stock varied from 1,010,533 mt to 897,275 mt for discount rates of 0.02 and 0.06, respectively. The breakeven biomass (X_2) at this price/cost ratio was 348,748 mt, and the wetfish fleet would earn positive net revenues at any biomass above that level. If the price cost ratio ever exceeds 0.6, the Pacific Fishery Management Council may face greater pressure to increase the reduction quota.

It seems unlikely that either the price/cost ratio or anchovy biomass would increase sufficiently to generate an economic interest in anchovy within the near future. The SSM says that the anchovy biomass jumped almost five fold from 1971 to 1974. Whether this really occurred and whether it could happen again is open to debate.

Given the current estimates of biomass it is probably fortunate that the exvessel price is low. Depressed prices for oil and fish meal are probably providing a more effective conservation incentive than any quota set by the Pacific Fishery Management Council.

References

Beauchamp, J. J. and J. S. Olson. 1973. "Corrections for Bias in Regression Estimates After Logarithmic Transformation." *Ecology*, 54(6): 1403-1407.

Beddington, J. R. and R. M. May. 1977. "Harvesting Natural Populations in a Randomly Fluctuating Environment." *Science*, (July 29): 463-465.

Burt, O. R. 1964. "Optimal Resource Use Over Time with an Application to Groundwater." *Managenment Science*, 11:80-93.

Burt, O. R. and R. G. Cummings. 1977. "Natural Resource Management, the Steady State and Approximately Optimal Decision Rules." *Land Economics*, 53:1-22.

Clark, C. W. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*(Second Edition). Wiley Interscience, New York, New York

Clark, C. W. and G. R. Munro. 1975. "Economics of Fishing and Modern Capital Theory: A Simplified Approach." *Journal of Environmental Economics and Management*, 2: 92-106.

Conrad, J. M. 1991. "A Bioeconomic Model of the Pacific Whiting." Administrative Report LJ-91-02, NMFS, Southwest Fisheries Science Center, La Jolla, California. (To be appear in the *Bulletin of Mathematical Biology*, 1992.)

Conrad, J. M. and C. W. Clark. 1987. *Natural Resource Economics: Notes and Problems*. Cambridge University Press, New York, New York.

Huppert, D. D. 1981. Economic Analysis for Northern Anchovy Management." in Lee G. Anderson, editor, *Economic Analysis for Fishery Management Plans*. Ann Arbor Science Publishers Inc., Ann Arbor, Michigan.

Huppert, D. D., MacCall, A. D., Stauffer, G. D., Parker, K. R., McMillan, J. A. and H. W. Frey. 1980. "California's Northern Anchovy Fishery: Biological and Economic Basis for Fishery Management." NOAA Technical Memorandum, NOAA-TM-NMFS-SWFC-1.

Huppert, D., Klingbeil, R., MacMillan, J. and R. Read. 1981. "California's Northern Anchovy Fishery for 1980/1981." NMFS, Southwest Fisheries Center, La Jolla, California.

Jacobson, L. D. and N. C. H. Lo. 1991. "Spawning Biomass of the Northern Anchovy in 1991." Administrative Report LJ-91-19, NMFS, Southwest Fisheries Science Center, La Jolla, California.

Jacobson, L. D. and C. J. Thomson. 1991. "Opportunity Costs and the Decision to Fish for Northern Anchovy." NMFS, Southwest Fisheries Science Center, La Jolla, California.

Jacobson, L. D. and C. J. Thomson. 1989. "Evaluation of Options for Managing Northern Anchovy - A Simulation Model." Administrative Report LJ-89-26, NMFS, Southwest Fisheries Center, La Jolla, California.

Kolberg, W. C. 1991. "Approach Paths to the Steady State: A Performance Test of Current-Period Decision Rule Solution Methods for Models of Renewable Resource Management." Working Paper, Department of Economics, Ithaca College, Ithaca, New York. (To appear in *Land Economics*.)

MacCall, A. D., Methot, R., Huppert, D. and R. Klingbeil. 1983. "Northern Anchovy Management Plan." Pacific Fishery Management Council, Portland, Oregon.

MacCall, A. D. 1978. "A Note on Production Modeling of Populations with Discontinuous Reproduction." *California Fish and Game*, 64(3): 225-227.

Methot, R. D. 1989. "Synthetic Estimates of Historical Abundance and Mortality for Northern Anchovy." in *Mathematical Analysis of Fish Stock Dynamics*, Edwards, E. F. and B. A. Megrey, eds, Symposium No. 6, AFS, Bethesda, Maryland.

Radovich, J and A. D. MacCall. 1979. "A Management Model of the Central Stock of Northern Anchovy." *CalCoFI Reports*, 20: 83-88.

Thomson, C., Cooney, C. and J. Morgan. 1990. "Status of the California Coastal Pelagic Fisheries in 1989." Administrative Report LJ-90-13, NMFS, Southwest Fisheries Science Center, La Jolla, California.

Table 1. The Exvessel Price (Dollars per Metric Ton) for Anchovy in the Reduction Fishery*

Year	Price
1974	$103
1975	$71
1976	$79
1977	$96
1978	$91
1979	$80
1980	$82
1981	$82
1982	$53
1983	$48
1984	$39
1985	$34
1986	$30
1987	$29
1988	$33
1989	$36
1990	$30

Source: The exvessel prices from 1974 to 1989 are from Jacobson and Thomson (1991). The 1990 price of $30/mt is from Thomson (personal communication 7/22/91).

Table 2. Estimates of Biomass and Total Harvest of Northern Anchovy from the Central Population*

Year	Biomass	Harvest
1964	341,640	11,565
1965	563,380	17,417
1966	567,990	47,637
1967	497,530	56,577
1968	415,700	35,007
1969	361,510	70,124
1970	353,910	120,830
1971	353,910	66,563
1972	724,430	98,041
1973	1,219,800	141,390
1974	1,766,100	125,153
1975	1,611,800	206,254
1976	1,275,300	195,275
1977	790,830	250,116
1978	568,970	157,471
1979	527,620	263,193
1980	799,730	302,031
1981	661,660	314,934
1982	459,500	229,464
1983	557,560	87,876
1984	319,300	108,420
1985	649,720	126,865
1986	698,590	101,921
1987	566,640	129,350
1988	329,050	84,886
1989	341,790	87,867
1990	299,410	8,149

*Source: The estimates of biomass and harvest are for the entire fishery (U.S. and Mexican) and are from Jacobson and Lo (1991), Tables 3 and 1, respectively.

Table 3. Season, Harvest of U.S. Reduction Fleet, Hours Fished and Average Biomass*

Season	U.S. Harvest for Reduction	Hours Fished	Average Biomass
1965/66	15,280	3,400	565,685
1966/67	34,112	7,567	532,760
1967/68	5,899	1,378	456,615
1968/69	25,447	6,376	388,605
1969/70	75,726	20,035	357,710
1970/71	73,258	19,544	353,910
1971/72	48,489	12,936	539,170
1972/73	68,510	13,822	972,115
1973/74	109,442	18,020	1,492,950
1974/75	106,851	15,229	1,688,950
1975/76	127,992	18,904	1,443,550
1976/77	96,592	15,630	1,033,065
1977/78	68,665	13,387	679,900
1978/79	49,340	10,938	548,295
1979/80	34,541	7,886	663,675
1980/81	60,563	11,756	730,695
1981/82	48,002	10,033	560,580
1982/83	5,704	1,374	508,530
1983/84	1,680	375	438,430
1984/85	71	20	484,510
1985/86	1,371	289	674,155
1986/87	38	8	632,615
1987/88	111	25	447,845
1988/89	234	64	335,420
1989/90	109	29	320,600

*Sources: Harvest for the seasons 1965/66 to 1980/81 are from Huppert et al. (1981) and have been converted from short tons to metric tons. Harvest for the seasons 1981/82 to 1989/90 are from Thomson et al. (1990). Estimates of the hours fished are from Jacobson (personal communication 7/17/91). Seasonal biomass is the two-year moving average of total biomass from Table 1.

Table 4. Estimates of Parameters of the Growth and Production Functions

The Growth Function: $X_{t+1} = aX_t^b e^{\varepsilon_t} - dY_t$

$\ln[X_{t+1} + dY_t] = \ln a + b \ln X_t + \varepsilon_t$ (Data from Table 2, d = 0.75)

Variable	Estimated Coefficient	Standard Error	t - ratio
ln a	1.6293	0.5119	3.1832
$\ln X_t$	0.88790	0.0386	23.003
rho	0.73028	0.13398	5.4508

$R^2 = 0.9824$ adj. $R^2 = 0.9817$ D.W. = 1.8305

$s^2 = 0.43626$ E -2

The Production Function: $H_j = B_j (1 - e^{-q E_j + \mu_j})$

$\ln[(B_j - H_j)/B_j) = \alpha - q E_j + \mu_j$ (Data from Table 3.)

Variable	Estimated Coefficient	Standard Error	t - ratio
α	0.15465 E -1	0.13869 E -1	1.1151
- q	- 0.95580 E -5	0.87647 E -6	- 10.905
rho_1	1.16124	0.17574	6.6078
rho_2	- 0.47739	0.17574	- 2.7165

$R^2 = 0.9119$ adj. $R^2 = 0.9081$ D.W. = 2.1373

Table 5. Optimal Biomass, Harvest, Effort and Net Revenue for Alternative Rates of Discount, Price and Cost

	$\delta = 0.02$	$\delta = 0.04$	$\delta = 0.06$
	$X^* = 1{,}522{,}566$	$X^* = 1{,}488{,}756$	$X^* = 1{,}460{,}424$
	$Y^* = 76{,}464$	$Y^* = 79{,}953$	$Y^* = 82{,}795$
$p = 30$	$E^* = 5{,}390$	$E^* = 5{,}775$	$E^* = 6{,}106$
$c = 300$	$\pi^* = 676{,},676$	$\pi^* = 665{,}997$	$\pi^* = 651{,}999$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 1{,}046{,}244$	$X_2 = 1{,}046{,}244$	$X_2 = 1{,}046{,}244$
	$X^* = 1{,}156{,}819$	$X^* = 1{,}102{,}997$	$X^* = 1{,}058{,}578$
	$Y^* = 108{,}107$	$Y^* = 111{,}498$	$Y^* = 114{,}014$
$p = 60$	$E^* = 10{,}264$	$E^* = 11{,}149$	$E^* = 11{,}922$
$c = 300$	$\pi^* = 3{,}407{,}002$	$\pi^* = 3{,}344{,}989$	$\pi^* = 3{,}264{,}010$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 523{,}122$	$X_2 = 523{,}122$	$X_2 = 523{,}122$
	$X^* = 1{,}010{,}533$	$X^* = 948{,}267$	$X^* = 897{,}275$
	$Y^* = 116{,}435$	$Y^* = 119{,}079$	$Y^* = 120{,}805$
$p = 90$	$E^* = 12{,}807$	$E^* = 14{,}039$	$E^* = 15{,}129$
$c = 300$	$\pi^* = 6{,}636{,}795$	$\pi^* = 6{,}505{,}315$	$\pi^* = 6{,}333{,}730$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 348{,}748$	$X_2 = 348{,}748$	$X_2 = 348{,}748$
	$X^* = 1{,}288{,}205$	$X^* = 1{,}241{,}625$	$X^* = 1{,}202{,}947$
	$Y^* = 98{,}374$	$Y^* = 102{,}051$	$Y^* = 104{,}918$
$p = 30$	$E^* = 8{,}311$	$E^* = 8{,}973$	$E^* = 9{,}547$
$c = 200$	$\pi^* = 1{,}288{,}982$	$\pi^* = 1{,}266{,}886$	$\pi^* = 1{,}237{,}996$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 697{,}496$	$X_2 = 697{,}496$	$X_2 = 697{,}496$
	$X^* = 1{,}010{,}533$	$X^* = 948{,}267$	$X^* = 897{,}275$
	$Y^* = 116{,}435$	$Y^* = 119{,}079$	$Y^* = 120{,}805$
$p = 60$	$E^* = 12{,}807$	$E^* = 14{,}039$	$E^* = 15{,}129$
$c = 200$	$\pi^* = 4{,}424{,}530$	$\pi^* = 4{,}336{,}876$	$\pi^* = 4{,}222{,}486$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 348{,}748$	$X_2 = 348{,}748$	$X_2 = 348{,}748$
	$X^* = 900{,}436$	$X^* = 831{,}182$	$X^* = 774{,}810$
	$Y^* = 120{,}710$	$Y^* = 122{,}407$	$Y^* = 123{,}165$
$p = 90$	$E^* = 15{,}059$	$E^* = 16{,}667$	$E^* = 18{,}112$
$c = 200$	$\pi^* = 7{,}852{,}077$	$\pi^* = 7{,}683{,}133$	$\pi^* = 7{,}462{,}398$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 232{,}499$	$X_2 = 232{,}499$	$X_2 = 232{,}499$

Table 5. continued

	$X^* = 1{,}010{,}533$	$X^* = 948{,}267$	$X^* = 897{,}275$
	$Y^* = 116{,}435$	$Y^* = 119{,}079$	$Y^* = 120{,}805$
$p = 30$	$E^* = 12{,}807$	$E^* = 14{,}039$	$E^* = 15{,}129$
$c = 100$	$\pi^* = 2{,}212{,}265$	$\pi^* = 2{,}168{,}438$	$\pi^* = 2{,}111{,}243$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 348{,}748$	$X_2 = 348{,}748$	$X_2 = 348{,}748$
	$X^* = 839{,}755$	$X^* = 766{,}198$	$X^* = 706{,}503$
	$Y^* = 122{,}242$	$Y^* = 123{,}228$	$Y^* = 123{,}261$
$p = 60$	$E^* = 16{,}459$	$E^* = 18{,}345$	$E^* = 20{,}059$
$c = 100$	$\pi^* = 5{,}688{,}596$	$\pi^* = 5{,}559{,}193$	$\pi^* = 5{,}389{,}768$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 174{,}374$	$X_2 = 174{,}374$	$X_2 = 174{,}374$
	$X^* = 773{,}734$	$X^* = 694{,}871$	$X^* = 631{,}012$
	$Y^* = 123{,}173$	$Y^* = 123{,}181$	$Y^* = 122{,}209$
$p = 90$	$E^* = 18{,}141$	$E^* = 20{,}415$	$E^* = 22{,}521$
$c = 100$	$\pi^* = 9{,}271{,}527$	$\pi^* = 9{,}044{,}834$	$\pi^* = 8{,}746{,}625$
	$X_1 = 614{,}553$	$X_1 = 516{,}729$	$X_1 = 435{,}914$
	$X_2 = 116{,}249$	$X_2 = 116{,}249$	$X_2 = 116{,}249$

Note: When $a = 5.111$ and $b = 0.888$, $X_{MSY} = 733{,}410$ and $MSY = 123{,}336$

Figure 1. The Approximate Location of the Three Subpopulations of the Northern Anchovy

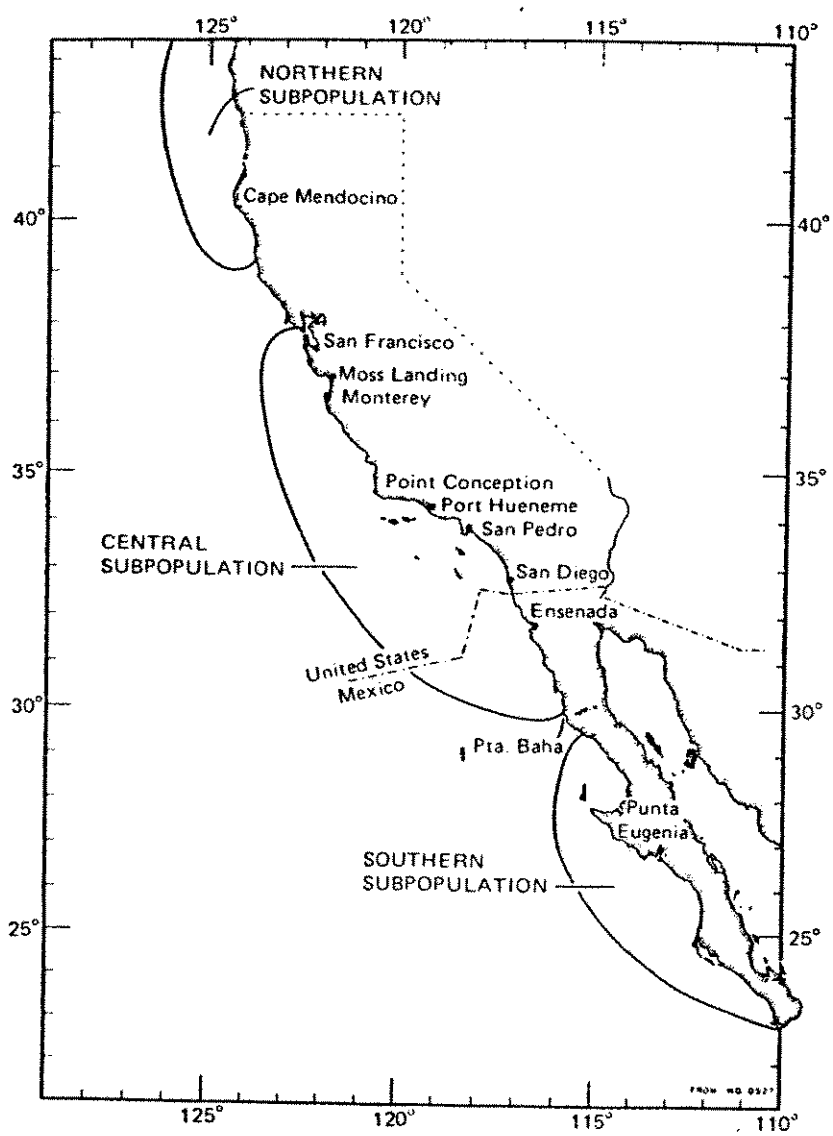


Figure 2. A Plot of Biomass from the SSM, Regression and Simulation

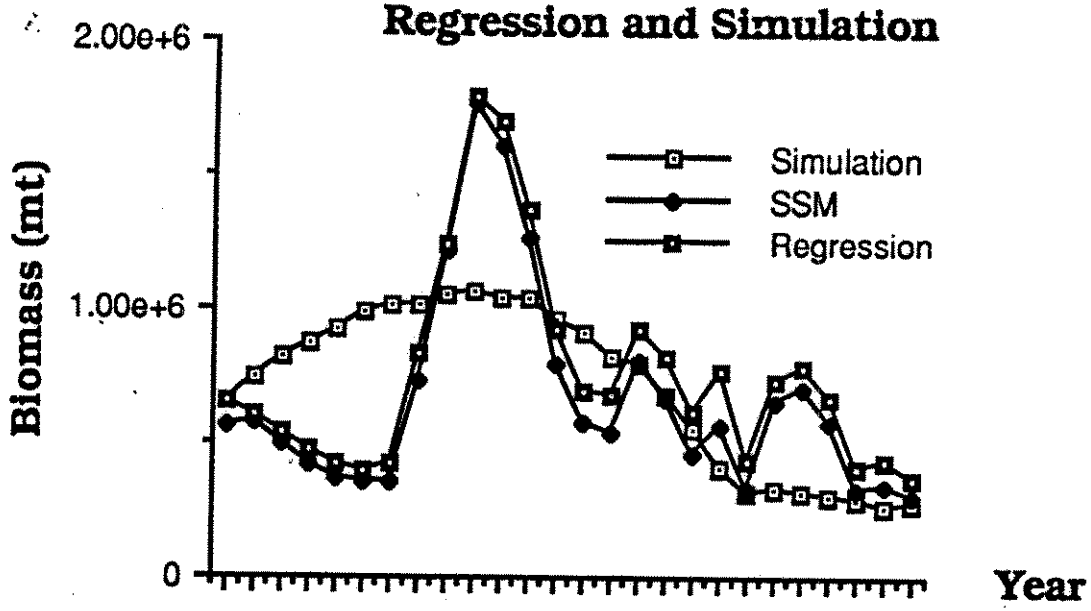
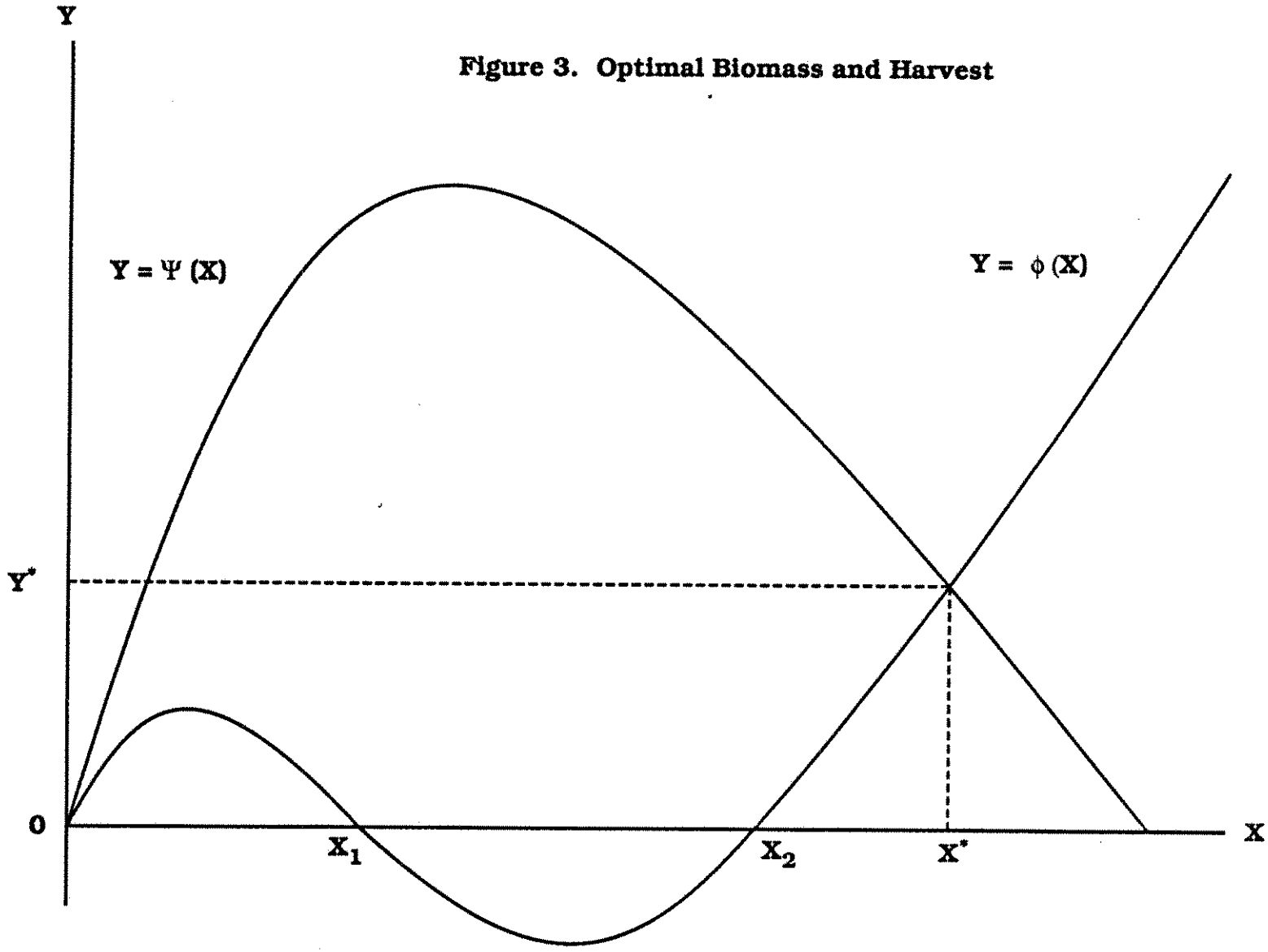


Figure 3. Optimal Biomass and Harvest



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