FISHERY MANAGEMENT:
THE CASE OF TUNA IN THE EASTERN TROPICAL ATLANTIC

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ABSTRACT

A simple bioeconomic model (the Gordon-Schaefer model) is estimated for three species of tuna in the Eastern Tropical Atlantic. The model conformed well to the data and afforded estimates of maximum sustainable yeild, bioeconomic and open access equilibria. Strong marginal stock effects were identified in all three fisheries, resulting in bioeconomic optima with stocks in excess of X_{MSY}. While all three fisheries appear to have been economically overfished (fishery rents being driven toward zero), Yellowfin and Skipjack stocks do not appear to be biologically overfished (stocks appear to be at or slightly above $X = K/2$). For Bigeye Tuna there was strong indication of both economic and biological overfishing. A management policy employing transferable quotas and landings taxes is examined. Such a policy has three advantages: (a) optimal yield will be harvested at least cost; (b) potential fishery rents may be distributed in a flexible fashion between West African and foreign flag vessels; and (c) a portion of the potential fishery rents may be captured by the management agency to defray the costs of administration, enforcement and research.

Key Words: Fishery Management, Bioeconomics, Tuna

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I. Introduction and Overview

This paper develops bioeconomic models for three species of tuna in the Eastern Tropical Atlantic (ETA). From a theoretical perspective it draws from the seminal work by Gordon (1954), Scott (1955) and Schaefer (1957), as well as the more recent capital-theoretic approach summarized by Clark and Munro (1975). Parameters of a Gordon-Schaefer model are estimated for each species, allowing one to identify maximum sustainable yields, open access equilibria, and bioeconomic optima. These equilibria are useful in evaluating the magnitude of recent landings and in suggesting policies which would establish and maintain the fishery in a more profitable state.

The next section describes the ETA tuna fishery, focusing on the countries participating in this fishery, effort, and catch. This is followed by a brief review of the basic bioeconomic model and the Gordon-Schaefer specification. The fourth section presents estimates for the various bioeconomic parameters and compares three steady state equilibria: maximum sustainable yield, open access, and the bioeconomic optimum. The fifth section examines landing taxes and transferable quotas as policies for managing the fishery and distributing rents among coastal and distant water fleets. The final section collects and qualifies the principal conclusions in light of the limitations inherent in lumped parameter (biomass) models.

II. The Tuna Fishery in the Eastern Tropical Atlantic

Harvests of tuna in the ETA are dominated by three species: Yellowfin Tuna (*Thunnus albacares*), Skipjack Tuna (*Katsuwonus pelamis*) and Bigeye Tuna (*Thunnus obesus*). These species are caught by vessels operating in an area roughly bounded by latitudes 30° North to 30° South and by longitude 30° West to the west coast of Africa (Figure 1).

The three commercial species are often mixed within a single school, thus precluding species selection by purse seiners and baitboats, whose gear is designed to harvest near-surface schools. Some species selectivity is achieved by locational choice within the ETA and by use of a third gear-type, longlining, which draws from deeper swimming schools dominated by Bigeye Tuna.

Modern commercial expoitation of Yellowfin and Skipjack Tuna within the ETA began in the mid-1950s. During that period pole-and-line boats from France and Spain moved into the waters off present-day Senegal. Their operations expanded, and by the early 1960s, they were fishing throughout the year, ranging from the Canary Islands south to Point Noire in present-day Zaire. During the 1960s, there was an influx of purse seiners registered in Japan, Korea, Taiwan, Panama, the United States and Norway. The bulk of their catch was sold to a single company and landed in Tema (Ghana), which developed into a major transshipment point.

Landings, effort and catch per unit effort (CPUE) for Yellowfin, Skipjack and Bigeye Tuna are shown in Tables 1-3 for 1967 through 1980. The early 1970s saw the formation of several joint ventures and a multinational alliance between France, Ivory Coast, Senegal and Morocco (FISM).[1/] Vessels from Korea and Panama joined to harvest all three species, and while their landings are indvidually reported, Ghana and Japan formed two jointly owned companies in 1972 and 1974.

Total Yellowfin landings range from a low of 53,000 metric tons (MT) in 1967 to a record high of 118,500 MT in 1978. Spain has displaced Japan as a major harvester of Yellowfin. This shift reflects the decision on the part of Japan to develop its longline fleet and reduce the number of purse seiners fishing surface stocks (primarily Yellowfin). The FISM alliance has been a dominant harvester of Yellowfin; its share ranging from a low of 35.9 percent in 1969 to a high of 48.3 percent in 1980.

Landings of Skipjack ranged from 19,000 MT in 1967 to 113,700 MT in 1977. Japan, the FISM alliance and Spain have accounted for 60 to 80 percent of the total Skipjack landings during the 1967-80 period. There has been a shift in the share of landings from Japan to Spain although the degree of displacement is less than that which occurred for Yellowfin.

Japan is the dominant harvester of Bigeye Tuna. Its share of total harvest has ranged from 14.1 to 59 percent, with an average of 37.3 percent during the 1967-80 period. Vessels from Korea, Panama and Taiwan have also been significant participants in the Bigeye fishery. Total landings of Bigeye have ranged from 9,600 MT in 1967 to 23,900 MT in 1973. Landings of Yellowfin and Skipjack have been two to six times larger than the landings of Bigeye, and in 1980 the Bigeye harvest of 13,600 MT was only 6.4 percent of the total for all three species.

The landings data in Tables 1-3 were compiled by the International Commission for the Conservation of Atlantic Tunas (ICCAT) based on reports from countries with fleets harvesting tuna in the ETA. ICCAT also keeps track of the number and type of vessels harvesting tuna. The effort levels reported in Tables 1-3 are measured in standard days (SDs) at sea, where the number of days fished by small seiners, baitboats and longliners have been converted to large-seiner-day equivalents.[2/] In many models of commercial fishing, and in the Schaefer-Gordon model to be discussed shortly, catch per unit effort will be proportional to the fish stock. Changes in CPUE would be indicative of changing stock abundance. For all three species CPUE has shown a declining trend during the 1967-80 period. Such trends would be associated with harvests in excess of growth (or recruitment) and may be symptomatic of overfishing.

Have the stocks of Yellowfin, Skipjack and Bigeye been reduced below the level which would sustain maximum yield; that is, has biological overfishing occurred? Has fishing effort increased to the point where fishery rents have been dissipated; that is, has economic overfishing occurred? Before we present the econometric and numerical analysis which will address these questions, we will briefly review the basic bioeconomic model.

III. Bioeconomics

With the development of the maximum principle economists gained a more powerful tool for analyzing dynamic allocation problems. This method saw immediate application to the theory of economic growth and subsequently to renewable and nonrenewable resources; and served to highlight the capital-theoretic aspects inherent in the management of resource stocks (Clark and Munro, 1975 and Clark, 1976).

For a single species fishery it is assumed that the resource can be adequately described by a single state variable $X(t)$ representing biomass. The instananeous rate of change in biomass is given by

$$\dot{X} = \frac{dX(t)}{d(t)} = F(X(t)) - Y(t) \tag{1}$$

where $\dot{X}(t)$ is the time derivative of the fish stock (biomass), $F(\cdot)$ is net natural growth, and $Y(t)$ is commercial harvest.

Let

$$\pi(t) = \pi(Y(t), X(t)) \tag{2}$$

represent the net revenues from commercial harvest $Y(t)$. Net revenues would depend on fish stock if the cost of harvest depends on stock abundance. Maximization of the present value of net revenues would entail maximization of

$$\pi = \int_0^\infty \pi(Y(t), X(t))\, e^{-\delta t}\, dt \tag{3}$$

subject to the equation describing the change in biomass and an initial condition on the fish stock $X(0) = X_0$. The instantaneous discount rate is denoted by δ.

The current value Hamiltonian for this problem is

$$H(t) = \pi(Y(t), X(t)) + \mu(t)[F(X(t)) - Y(t)] \tag{4}$$

where $\mu(t)$ is the current value shadow price associated with an incremental change in the fish stock. The first order conditions for a maximum require

$$\frac{\partial H(t)}{\partial Y(t)} = \frac{\partial \pi(\cdot)}{\partial Y(t)} - \mu(t) = 0 \tag{5}$$

$$\dot{\mu}(t) = \frac{-\partial \pi(\cdot)}{\partial X(t)} + \mu(t)[\delta - F'(\cdot)] \tag{6}$$

$$\dot{X} = F(\cdot) - Y(t) \tag{7}$$

In steady state $\dot{\mu}(t) = \dot{X}(t) = 0$ and (5) and (6) imply

$$F'(\cdot) + \frac{\frac{\partial \pi(\cdot)}{\partial X}}{\frac{\partial \pi(\cdot)}{\partial Y}} = \delta \tag{8}$$

which is a fundamental equation for the basic bioeconomic model. The first term on the left hand side of equation (8) is the rate of change in net growth associated with an increment to the fish stock. The second term is referred to as the marginal stock effect. Together they sum to what has been called the resource's own rate of return. In steady state the optimal stock equates the resource's own rate of return to the market rate obtainable on other assets (Clark and Munro 1975, p.96).

The Gordon-Schaefer model presumes that equations (1) and (2) take the following form:

$$\dot{X} = \frac{dX(t)}{d(t)} = rX(t)[1 - X(t)/K] - Y(t) \tag{9}$$

and

$$\pi(t) = [p- \frac{c}{qX(t)}] Y(t) \quad . \tag{10}$$

Equation (9) is the logistic growth curve while (10) is the expression for net revenues which results when;(a) the per unit price for fish and the per unit cost for effort are constant and denoted by p and c respectively, and (b) the production function for the fishery is of the form

$$Y(t) = qE(t)X(t) \tag{11}$$

where E(t) is effort and q is referred to as the catchability coefficient.

For the Gordon -Schaefer model equation (8) leads to a quadratic equation where the optimal stock, X*, is the positive root and depends on the bioeconomic parameters c, p, q, δ, r, and K according to

$$X^* = \frac{K}{4}\left[\left(\frac{c}{qpK} + 1 - \frac{\delta}{r}\right) + \sqrt{\left(\frac{c}{qpK} + 1 - \frac{\delta}{r}\right)^2 - \frac{8c\delta}{qpKr}}\right] . \tag{12}$$

Alternatively, one could define steady state in terms of the two equation system:

$$Y = \phi(X) = [\delta - r(1 - 2X/K)][X(qpX/c - 1)], \tag{13}$$

and

$$Y = rX\,(1 - X/K) \quad . \tag{14}$$

Equation (13) has been referred to as the "catch locus" (Gould 1972), while equation (14) is the sustainable yield curve equating harvest to logistic growth. Three catch loci and a sustainable yield curve are drawn in Fiqure 2. The catch locus denoted as $\phi_1(X)$ might result from a combination of a high discount rate, low (stock insensitive) harvest costs, and high market value. Under such circumstances, it may be optimal to harvest the resource to extinction.[3/] Locus $\phi_2(X)$ shows a situation where the marginal stock effect is greater than the discount rate. It is optimal to maintain a stock in excess of X_{MSY} ($X^* > \frac{K}{2}$ for logistic growth) because of the reduced harvest cost associated with larger stocks. Finally, $\phi_3(X)$ might correspond to a situation of high harvest cost and low market price making commercial harvest unprofitable.($X^* = K$, its environmental maximum).

In addition to the bioeconomic optimum occurring at the intersection of a catch locus and the sustainable yield curve it will be useful to note two other equilibria: maximum sustainable yield and open access. For the logistic growth model, maximum sustainable yield is denoted $Y_{MSY} = \frac{rK}{4}$ occurring at $X_{MSY} = \frac{K}{2}$. Open access equilibrium occurs when $\pi(\cdot) = 0$ (fishery rents are dissipated). For positive stock and harvest (no extinction) this occurs at $X_\infty = \frac{c}{pq}$.

We now turn to estimates of the bioeconomic parameters for tuna in the ETA.

IV. Empirical Results

A yield function for a single species fishery relates equilibrium harvest to effort. For the Schaefer-Gordon model specified in the preceding section, the yield function takes the form:

$$Y = qKE(1 - qE/r) \quad (15)$$

or

$$U = \alpha - \beta E \quad (16)$$

where U is catch per unit effort, $\alpha = qK$, and $\beta = q^2K/r$. Estimates of α and β can be obtained using ordinary least squares and the data contained in Tables 1 - 3.

The catchability coefficient q is estimated independently using the integral method described by Fox (1975).[4/] Estimates for α, β, q, r, and K, along with supporting statistics, are given in Table 4 for Yellowfin, Skipjack, and Bigeye Tuna in the ETA. The Gordon-Schaefer specification would seem to conform well to the data. Estimates of α and β are of the expected sign and significant for all three species. The Durban-Watson statistics do not indicate autocorrelation.

Estimates for the cost of a standard day at sea in the ETA were not available. Recall that the effort of small purse seiners, baitboats and longliners had been converted to large seiner equivalents by using fishing power or daily-catch-rate weighting factors. The cost of operating a large purse seiner in the Eastern Tropical Pacific (ETP) has been examined by Flagg (1977), while baitboat costs in the ETP were estimated by the U.S. Bureau of Commercial Fisheries (1970). As with land-based firms, both fixed and variable cost components are present. Fixed costs occur regardless of the level of fishing effort, and include interest charges on vessel, equipment and gear, insurance premiums, depreciation, moorage and certain maintenance. Variable costs are associated with fishing and would include such items as fuel, oil, food and other maintenance.[5/] Estimates of cost per day for large seiners in the ETP were adjusted for general inflation and the more rapid escalation in fuel prices. Bioeconomic and open access equilibria were then calculated for \$500.00 cost increments for c = \$2000/SD to c = \$3500/SD in 1980 dollars.

The market prices for Yellowfin, Skipjack and Bigeye Tuna are recorded by the National Marine Fisheries Service (NMFS) Market News Service at Terminal Island, California. Yellowfin and Bigeye Tuna fetch the same price while Skipjack prices were \$50 to \$100 less per metric ton during the 1967-80 period. The 1980 average monthly prices for Yellowfin/Bigeye and for Skipjack were \$1300 and \$1200 respectively.

Sensitivity of the bioeconomic optimum was also tested with regard to variation in the discount rate, δ. It was varied in 0.05 increments from $\delta = 0.00$ to $\delta = 0.20$. Tables 5 and 6 show maximum sustainable yield (MSY), bioeconomic and open access equilibria for Yellowfin and Skipjack Tuna in the ETA. For both species we note that the optimal stock decreases with increases in the discount rate (δ) and increases with increases in the unit cost of effort (c). The marginal stock effect is positive and of a greater order of magnitude than the discount rate. Thus, the bioeconomic equilibria occur at stock levels in excess of X_{MSY}. These equilibria are similar to (X^*,Y^*) at the intersection of $\phi_2(\cdot)$ and the sustainable yield curve in Figure 2. For Yellowfin, with the exception of when c = \$3500, all open access equilibria occur at stock levels less than X_{MSY}. At such equilibria both biological $(X_\infty < X_{MSY})$ and economic $(\pi = 0)$ overfishing is said to occur. When c = \$3500, economic overfishing occurs $(\pi = 0)$ but biological does not $(X_\infty > X_{MSY})$.

For Skipjack Tuna both bioeconomic and open access equilibria occur at stocks in excess of X_{MSY}. Thus biological overfishing is neither optimal nor results from open access status. Open access stocks are less than the bioeconomic $(X_\infty < X^*)$ for all values of δ, with the higher stocks associated with the bioeconomic equilibria reducing harvest cost and producing positive fishery rents $(\pi > 0)$.

For Bigeye Tuna the initial cost vector lead to zero fishing (X = K) for both bioeconomic and open access equilibria. The catch locus, similar to $\phi_3(\cdot)$ in Figure 2, did not intersect the sustainable yield curve at a positive yield. Recall that the predominant source of Bigeye harvests were from longliners. Longline vessels are smaller, and the "passive" nature of the fishing technology employed make them less costly to operate than the larger purse seiners which require considerable power when hauling back after setting the seine.[6/] In the conversion to large seiner equivalents the catch-per-day weighting procedure may result in an over-estimation of fishing costs for longliners and baitboats within the Big-eye fishery. Revenues from longline trips were examined and estimates for the unit cost of effort were based on a fraction (about 75 percent) of gross receipts, leaving the remaining portion of gross revenues to cover other fixed costs. This procedure yielded an estimate of $517 as the cost of an equivalent day. Bracketing this cost estimate with the vector c = [$400, $500, $600, $700] leads to the MSY, bioeconomic and open access equilibria shown in Table 7. Again, we see significant marginal stock effects with $X^* > X_{MSY}$ for all combinations of δ and c. As with Yellowfin, open access status leads to equilibria with stocks less than MSY for all but the highest cost estimate (c = $700).

In comparing the estimates of MSY to the time series for total landings contained in Tables 1 through 3, one observes landings rates for Yellowfin and Skipjack which would be associated with stock reductions from X(t)=K toward $X(t) = X_{MSY} = K/2$. While these species would appear to be economically overfished, they would not appear to be biologically overfished. For Bigeye, however, an examination of landings relative to MSY would indicate a movement from X(t) = K to X(t) < K/2, with stocks considerably below all bioeconomic optima. Thus, both biological and economic overfishing would seem to have occurred during the 1967-80 period, and neither biologists nor economists would be sanguine about the current status of Bigeye stocks.

V. Management Policies

In managing fish stocks, particularly transboundary fish stocks such as salmon and tuna, distributional issues often overshadow efficiency issues. This is most certainly the case for tuna in the ETP, where extended jurisdiction by Latin American countries has led to seisure of U.S. registered vessels and confiscation of catch and seine (which may take \$300,000 and several months to replace). Distributional issues in the ETA have not reached the level of international controversy and rancor found in the ETP, but questions are being raised by West African nations as to how they might secure a greater share of the wealth generated by tuna stocks migrating through their coastal waters.

Economists have strongly recommended transferable quotas on the grounds that they are: (a) efficient, in the sense that the aggregate quota would be harvested at least cost; and (b) flexible, in the sense that they may be distributed initially to achieve any agreed-upon distribution of prospective fishery rents (Molony and Pearse 1979). In addition Clark (1980) has noted that individual quotas can be used in conjunction with a system of landings taxes to allow recapture of some proportion of fishery rents to help defray the costs of resource management and research. In particular, Clark notes that at a bioeconomic optimum

$$P_* + \tau = \mu , \tag{17}$$

where P_* is the equilibrium price emerging from the market for transferable quotas, τ is the landings tax rate, and μ is the current value shadow price defined by

$$\mu = [p - \frac{c}{qX^*}] . \tag{18}$$

For Yellwofin Tuna with c = \$3000 and $\delta = 0.10$, we saw that $X^* = 255.07 \times 10^3$MT, $Y^* = 89.96 \times 10^3$MT, and $E^* = 25.71 \times 10^3$SDs. The current value shadow price would be μ = \$442.75/MT. Suppose the aggregate quota of $Y^*= 89.96\times10^3$MT was distributed among a group of West African and foreign flag nations according to some formula. Suppose further that ICCAT levied a \$20/MT landings tax (τ = \$20/MT). Then the market quota price would be \$342.75/MT and ICCAT would generate \$1,799,200 to support administration, enforcement and research.

The formula for distributing the transferable quotas and the selection of a landings tax rate would undoubtedly be the subject of considerable debate. The historical share of landings by a country, joint venture or alliance would presumably influence the quota share formula. The formula could be revised periodically to reflect changes in the ability and interest of West African and foreign flag nations to harvest tuna in the ETA. The smaller West African countries with only artisanal fisheries and no previous commercial (offshore) harvesting capacity might be allocated a share of the total quota. Such countries would presumably sell their quotas to countries or companies who wish to harvest more than their initial allocation. The proceeds from sale of their quotas could be used to finance commercial vessels, thereby developing an ability to harvest offshore stocks in the future, or they may be directed toward other resource development or social projects.

VI. Conclusions and Caveats

A simple bioeconomic model (the Gordon-Schaefer model) was estimated with data for three species of tuna in the Eastern Tropical Atlantic. Statistically, the model conformed well to the data and afforded estimates of maximum sustainable yield, bioeconomic, and open access equilibria. Strong marginal stock effects were identified in all three fisheries, resulting in bioeconomic optima with stocks in excess of X_{MSY}. While all three fisheries appear to have been economically overfished, (fishery rents being driven toward zero), Yellowfin and Skipjack stocks do not appear to be biologically overfished (stocks would appear to be at or slightly above $X = K/2$). For Bigeye Tuna there was strong indication of both economic and biological overfishing and this stock may warrant special management attention from the International Commission for Conservation of Atlantic Tuna (ICCAT).

A management program based on both transferable quotas and landings taxes would promote the least cost harvest of optimal yield and afford a flexible mechanism for distributing potential fishery rents. Rather modest landings taxes seemed capable of generating sufficient revenues to allow for administration, enforcement and research by a management authority.

Biomass models, such as the Schaefer-Gordon model, are not capable of incorporating age or sex-specific characteristics of a fish population. Where these characteristics are important, a multiple cohort model (Conrad 1982) or sex-selective model (Clark and Tait 1982) would be required.

It is further the case that the three species of tuna, treated independently in this paper, may compete for a common food source. Models with interspecific competition and multi-trophic level predation (including harvesting by man) are complex on a purely biological basis, making bioeconomic analysis a formidable undertaking with only limited progress to date (May et al., 1979).

In light of these and other extenuating factors the empirical results and conclusions presented here should be regarded as preliminary. They are, hopefully, a useful first step; one which places the Eastern Tropical Atlantic tuna fisheries within a bioeconomic perspective and will help to define future management, distributional, and research issues.

FOOTNOTES

1/ During certain years this alliance also included Portugal. Portugese landings were never more than a small fraction of the total landings by the alliance and limited to Yellowfin and Bigeye Tuna. Thus the landings attributed to the FISM alliance may include minor amounts of Yellowfin and Bigeye caught by Portugal.

2/ It was assumed that the fishing power of a small seiner was 0.48 of a large seiner (Fonteneau and Cayré 1981). Average daily catch rates for baitboats and longliners were divided by the average daily catch rate for large seiners and the resulting fractions were used to weight (convert) baitboat and longline days into large-seiner-day equivalents. Baitboats and longliners were assumed to spend an average of 231 days at sea per year, while large and small seiners were assumed to spend 219 and 198 days per year at sea, respectively.

3/ Clark (1976, p.61) shows that extinction is optimal if both $p \geq c(0)$ and $\delta > 2F'(0)$, where $c(0)$ denotes the cost of harvesting the last surviving member of the population.

4/ For the Gordon-Schaefer model, it can be shown that

$$\frac{dU}{dt} = qU(\hat{\alpha}/\hat{\beta} - E^* - U/\hat{\beta}) \qquad \text{(a)}$$

or

$$\frac{dU}{U(\hat{\alpha}/\hat{\beta} - E^* - U/\hat{\beta})} = q dt \ . \qquad \text{(b)}$$

In the discrete time analogue used for estimating q, E^* is the effective effort exerted between years t and t+1 ; i.e. $E^* = (E_t + E_{t+1}) / 2$. The integral of (b) after rearranging some terms is

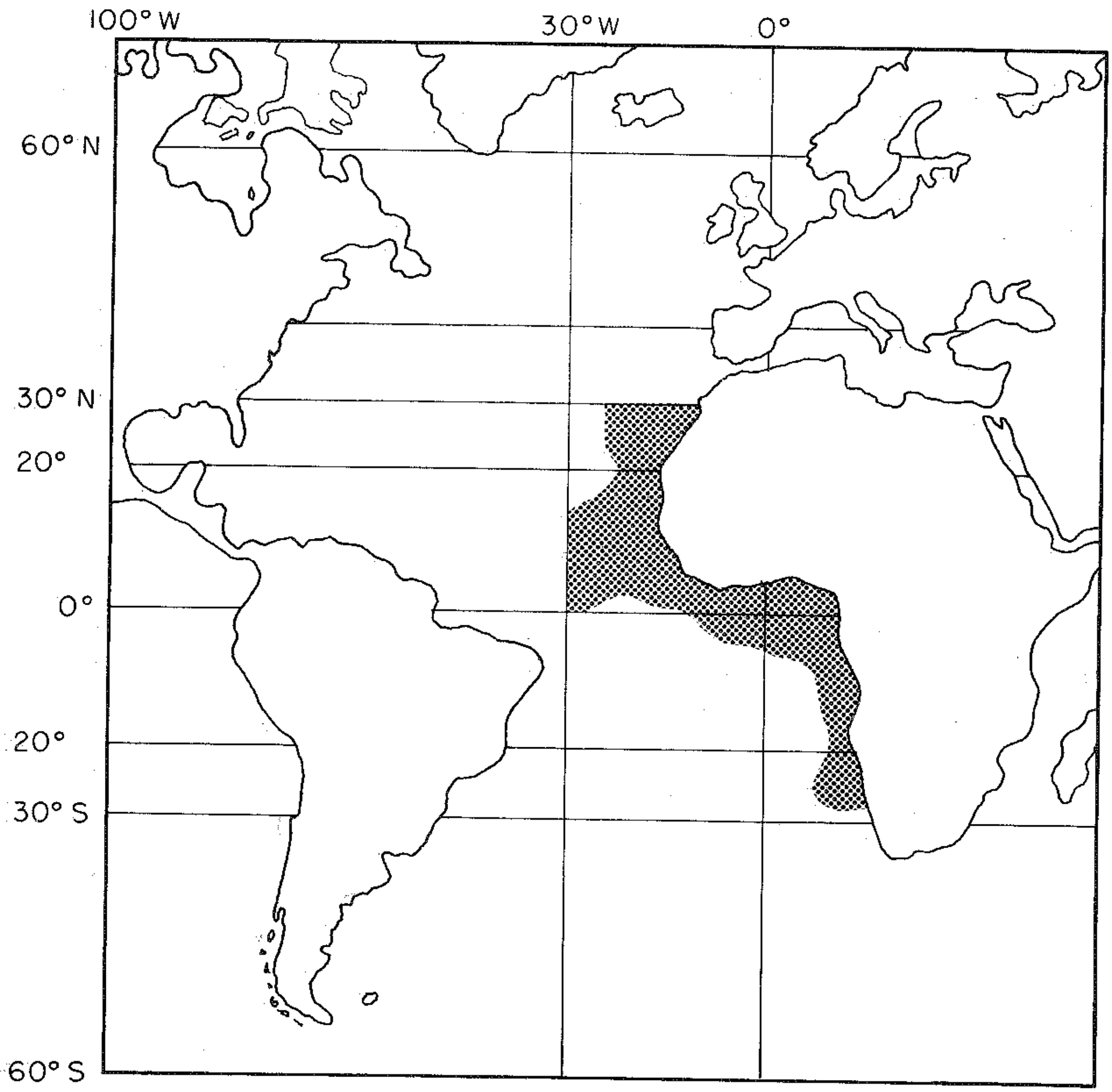
$$\hat{q}_t = \ln[|(Z\bar{U}_t^{-1} - \frac{1}{\hat{\beta}})/(Z\bar{U}_{t+1}^{-1} - \frac{1}{\hat{\beta}})|]/Z \ , \qquad \text{(c)}$$

where $Z = \frac{\hat{\alpha}}{\hat{\beta}} - E^*$. Equation (c) is a sequential estimator for q. A priori one would expect $q>0$. The absolute value operator in equation (c) will guarantee positive estimates of q even when catch per unit effort is trending in one direction. With a time series for $\hat{q}_t$, an integral estimate can be obtained by taking the arithmetic or geometric mean. The arithmetic mean was used to derive the estimates of $\hat{q}$ reported in Table 4.

5/ Wages may be paid to certain crew members, but most would receive compensation for their work during the trip by a crewshare (or lay) system where members receive a share of net revenues. For a discussion of the theory of share contracting and its role in spreading the risk inherent in fishing, see Sutinen (1975).

6/ Using buoy and anchor weights, longliners will suspend a line horizontal to the water column. From this long line, shorter lines with weights and baited hooks are dropped into the water column. After an appropriate period of time the vessel returns, retrieving each fishing line to remove tuna, rebait, or collect gear for deployment at a new location.

FIGURE I. LOCATION MAP FOR THE EASTERN TROPICAL ATLANTIC TUNA FISHERY*



* Cross hatching indicates area of greatest fishing intensity

FIGURE 2. CATCH LOCI AND THE SUSTAINABLE YIELD CURVE IN THE SCHAEFER-GORDON MODEL

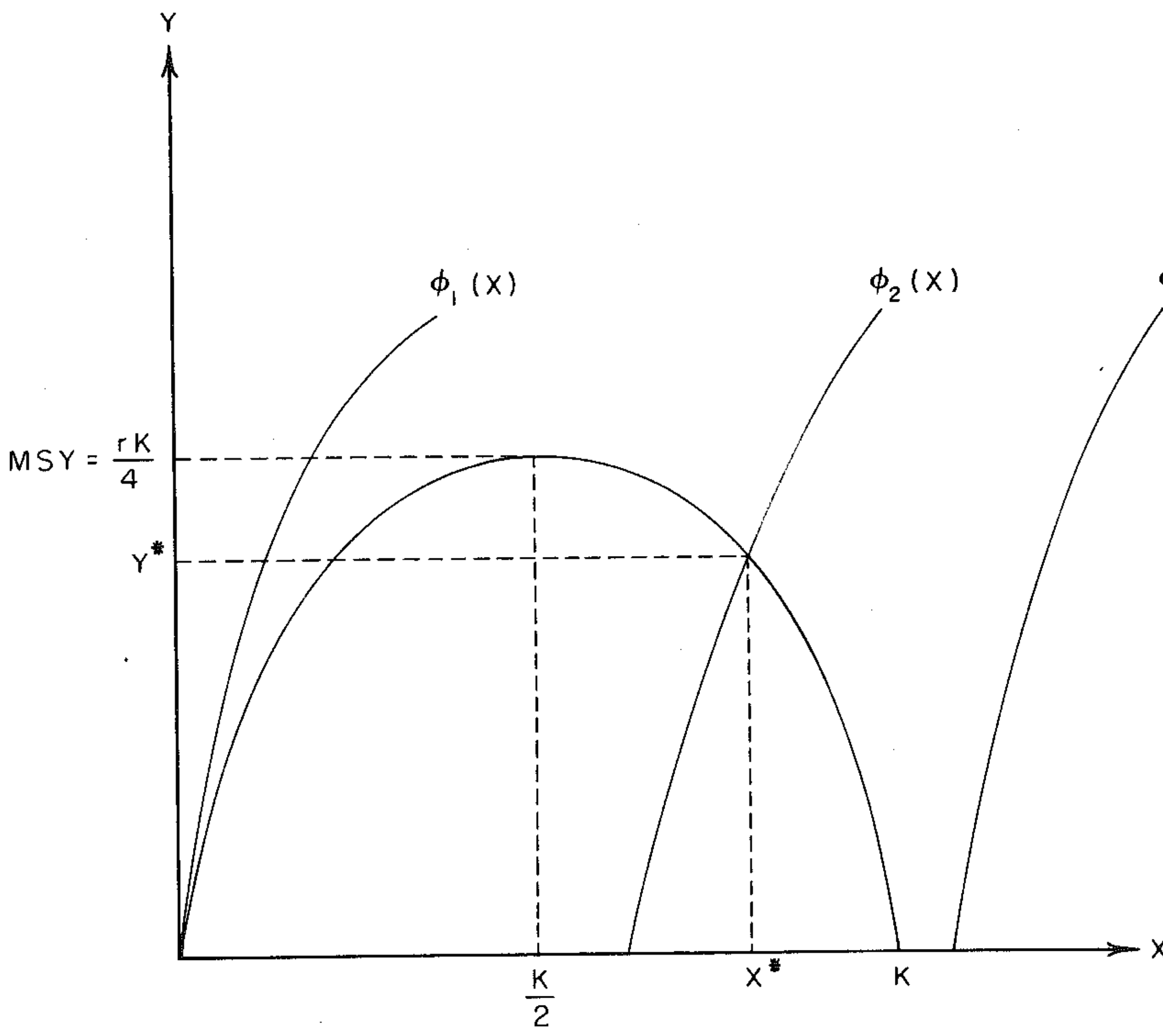


TABLE 1: LANDINGS, EFFORT, AND CATCH PER UNIT EFFORT FOR YELLOWFIN TUNA IN THE EASTERN TROPICAL ATLANTIC†

YEAR	LANDINGS BY NATION, JOINT VENTURE, OR MULTINATIONAL ALLIANCE*								TOTAL LANDINGS	EFFORT (SDs)	CATCH PER UNIT EFFORT (CPUE)
	GHANA	JAPAN	KOREA / PANAMA	FISM	ANGOLA	SPAIN	USA	OTHERS			
1967	0	16,600 (31.2)	0	23,400 (44)	900 (1.7)	3,100 (5.8)	900 (1.7)	8,300 (15.6)	53,200 (100)	12,800	4.15
1968	0	19,500 (26.2)	1,600 (2.2)	31,400 (42.2)	1,100 (1.5)	3,300 (4.4)	5,800 (7.8)	11,700 (15.7)	74,400 (100)	15,500	4.78
1969	0	12,100 (14.7)	4,200 (5.1)	29,500 (35.9)	400 (0.5)	5,800 (7.1)	18,800 (22.9)	11,300 (13.8)	82,100 (100)	21,400	3.83
1970	0	4,400 (7.2)	9,300 (15.2)	24,700 (40.4)	300 (0.5)	7,100 (11.6)	9,000 (14.7)	6,400 (10.4)	61,200 (100)	19,900	3.08
1971	0	5,600 (9.7)	6,900 (11.9)	26,800 (46.2)	500 (0.9)	7,600 (13.1)	3,800 (6.6)	6,800 (11.7)	58,000 (100)	15,100	3.84
1972	0	8,300 (10.5)	8,200 (10.4)	32,100 (40.7)	600 (0.8)	9,300 (11.8)	12,000 (15.2)	8,400 (10.6)	78,900 (100)	18,600	4.24
1973	100 (0.1)	9,000 (10.6)	17,900 (21.1)	32,300 (38)	600 (0.7)	14,000 (16.5)	3,000 (3.5)	8,000 (9.4)	84,900 (100)	31,900	2.66
1974	300 (0.3)	8,600 (8.9)	17,500 (18.2)	39,200 (40.8)	800 (0.8)	15,700 (16.3)	5,600 (5.8)	8,600 (8.9)	96,300 (100)	30,400	3.17
1975	700 (0.6)	2,900 (2.6)	13,700 (12.5)	48,000 (43.9)	100 (0.1)	24,800 (22.7)	14,000 (12.8)	5,300 (4.8)	109,500 (100)	41,600	2.63
1976	800 (0.7)	5,200 (4.5)	12,900 (11.3)	54,200 (47.4)	1,000 (0.9)	33,300 (29.1)	1,700 (1.5)	5,300 (4.6)	114,400 (100)	40,200	2.84
1977	600 (0.5)	2,700 (2.4)	12,700 (11.1)	51,300 (44.9)	1,900 (1.7)	33,500 (29.3)	6,400 (5.6)	5,100 (4.5)	114,200 (100)	42,700	2.68
1978	300 (0.3)	1,700 (1.4)	10,100 (8.5)	56,500 (47.7)	2,000 (1.7)	35,300 (29.8)	8,100 (6.8)	4,500 (3.8)	118,500 (100)	54,900	2.16
1979	300 (0.3)	900 (0.8)	6,000 (5.2)	51,000 (44.3)	800 (0.7)	40,300 (35)	2,900 (2.5)	12,900 (11.2)	115,100 (100)	60,200	1.91
1980	300 (0.3)	1,000 (1)	2,800 (2.8)	48,300 (48.3)	0	35,700 (35.7)	4,800 (4.8)	7,200 (7.1)	100,100 (100)	57,700	1.73

†Source: International Commission for the Conservation of Atlantic Tunas (ICCAT).
*Landings are in metric tons (MT). Percentage of total catch is given in parentheses.

TABLE 2: LANDINGS, EFFORT, AND CATCH PER UNIT EFFORT FOR SKIPJACK TUNA IN THE EASTERN TROPICAL ATLANTIC†

YEAR	LANDINGS BY NATION, JOINT VENTURE OR MULTINATIONAL ALLIANCE*								TOTAL LANDINGS	EFFORT (SDs)	CATCH PER UNIT EFFORT (CPUE)
	GHANA	JAPAN	KOREA/PANAMA	FISM	ANGOLA	SPAIN	USA	OTHERS			
1967	0	5,900 (31.1)	0	5,300 (27.9)	2,000 (10.5)	3,800 (20)	500 (2.6)	1,500 (7.9)	19,000 (100)	8,300	2.28
1968	0	13,600 (30.5)	0	12,400 (27.8)	4,200 (9.4)	9,500 (21.3)	3,200 (7.2)	1,700 (3.8)	44,600 (100)	12,300	3.62
1969	0	5,600 (21.3)	0	6,500 (24.7)	1,800 (6.8)	7,200 (27.4)	4,700 (17.9)	500 (1.9)	26,300 (100)	9,400	2.81
1970	0	11,000 (23.5)	0	13,200 (28.1)	900 (1.9)	8,300 (17.7)	11,800 (25.2)	1,700 (3.6)	46,900 (100)	15,900	2.94
1971	0	17,900 (24.7)	0	20,000 (27.6)	1,900 (2.6)	14,900 (20.6)	16,200 (22.4)	1,500 (2.1)	72,400 (100)	23,400	3.09
1972	0	13,500 (19)	700 (1)	18,600 (26.3)	1,500 (2.1)	24,200 (34.1)	12,200 (17.2)	200 (0.3)	70,900 (100)	24,100	2.95
1973	100 (0.1)	14,500 (19.9)	1,100 (1.5)	12,700 (17.5)	1,300 (1.8)	21,300 (29.3)	21,200 (29.1)	600 (0.8)	72,800 (100)	25,000	2.91
1974	700 (0.6)	19,600 (17.3)	3,100 (2.7)	28,500 (25.3)	3,400 (3)	37,000 (32.7)	20,000 (17.7)	800 (0.7)	113,000 (100)	46,200	2.45
1975	1,300 (2.3)	3,800 (6.6)	6,300 (11)	13,300 (23.3)	600 (1)	18,900 (33)	7,400 (12.9)	5,700 (9.9)	57,300 (100)	26,600	2.15
1976	2,100 (2.9)	15,000 (20.5)	4,400 (6)	18,600 (25.4)	1,500 (2)	17,400 (23.8)	1,800 (2.5)	12,400 (16.9)	73,200 (100)	40,100	1.82
1977	3,500 (3.1)	16,800 (14.8)	7,600 (6.7)	33,600 (29.6)	3,800 (3.3)	27,700 (24.3)	5,900 (5.2)	14,800 (13)	113,700 (100)	68,700	1.65
1978	2,600 (2.6)	14,600 (14.6)	11,100 (11.1)	28,300 (28.2)	3,200 (3.2)	25,500 (25.4)	6,800 (6.8)	8,100 (8.1)	100,200 (100)	63,800	1.57
1979	3,900 (4.6)	14,700 (17.5)	13,800 (16.4)	21,100 (25.1)	3,600 (4.3)	19,800 (23.6)	2,100 (2.5)	5,000 (6)	84,000 (100)	68,500	1.23
1980	not available	20,000 (20.6)	not available	30,000 (30.9)	5,100 (5.2)	33,500 (34.5)	3,500 (3.6)	5,100 (5.2)	97,200 (100)	79,600	1.22

†Source: International Commission for the Conservation of Atlantic Tunas (ICCAT).
*Landings are in metric tons (MT). Percentage of total catch is given in parentheses.

TABLE 3: LANDINGS, EFFORT, AND CATCH PER UNIT EFFORT FOR BIGEYE TUNA IN THE EASTERN TROPICAL ATLANTIC[†]

YEAR	LANDINGS BY NATION, JOINT VENTURE OR MULTINATIONAL ALLIANCE*								TOTAL LANDINGS	EFFORT (SDs)	CATCH PER UNIT EFFORT (CPUE)
	GHANA	JAPAN	KOREA/PANAMA	FISM	TAIWAN	SPAIN	USA	OTHER			
1967	0	5,700 (59)	100 (1)	0	1,900 (20)	0	0	1,900 (20)	9,600 (100)	11,200	0.86
1968	0	7,200 (54)	200 (1.5)	0	3,800 (28.5)	0	0	2,100 (16)	13,300 (100)	15,200	0.87
1969	0	9,500 (52)	1,400 (7.7)	400 (2)	4,500 (24.8)	0	100 (0.5)	2,300 (13)	18,200 (100)	16,700	1.09
1970	0	4,800 (33)	3,500 (24)	700 (5)	2,400 (16)	100 (0.7)	200 (1.4)	2,900 (19.9)	14,600 (100)	23,100	0.63
1971	0	8,100 (35.4)	5,500 (24)	800 (3.5)	3,100 (13.5)	200 (0.9)	500 (2.2)	4,700 (20.5)	22,900 (100)	33,300	0.69
1972	0	7,900 (38.2)	4,400 (21.3)	900 (4.2)	4,200 (20.3)	200 (1)	200 (1)	2,900 (14)	20,700 (100)	27,600	0.75
1973	0	10,800 (45.2)	3,000 (12.6)	2,200 (9.2)	2,500 (10.4)	400 (1.7)	100 (0.4)	4,900 (20.5)	23,900 (100)	35,400	0.68
1974	100 (0.5)	5,400 (27.7)	4,000 (20.5)	1,600 (8.2)	2,000 (10.3)	700 (3.6)	900 (4.6)	4,800 (24.6)	19,500 (100)	37,800	0.52
1975	100 (0.6)	5,100 (28.7)	4,000 (22.5)	600 (3.4)	2,500 (14)	200 (1.1)	100 (0.6)	5,200 (29.1)	17,800 (100)	45,200	0.39
1976	100 (0.6)	2,300 (14.1)	4,100 (25.2)	600 (3.7)	2,900 (17.8)	400 (2.5)	0	5,900 (36.1)	16,300 (100)	47,800	0.34
1977	200 (1.1)	4,800 (26.2)	3,000 (16.4)	1,300 (7.1)	2,700 (14.8)	800 (4.4)	300 (1.6)	5,200 (28.4)	18,300 (100)	54,900	0.33
1978	100 (0.5)	4,100 (22.3)	5,600 (30.4)	1,100 (6)	2,000 (10.9)	600 (3.3)	200 (1.1)	4,700 (25.5)	18,400 (100)	70,700	0.26
1979	100 (0.5)	7,400 (36.6)	5,500 (27.2)	700 (3.5)	1,900 (9.4)	600 (3)	200 (1)	3,800 (18.8)	20,200 (100)	79,200	0.25
1980	not available	6,800 (50)	5,100 (37.5)	600 (4.4)	200 (1.5)	600 (4.4)	200 (1.5)	100 (0.7)	13,600 (100)	74,600	0.18

[†]Source: International Commission for the Conservation of Atlantic Tunas (ICCAT)
*Landings are in metric tons (MT). Percentage of total catch is given in parentheses.

TABLE 4: ESTIMATES OF α, β, q, r, and K FOR TUNA IN THE EASTERN TROPICAL ATLANTIC

SPECIES	$\hat{\alpha}$	$\hat{\beta}$	$\hat{q}$ ($\times 10^{-2}$)	$\hat{r}$	$\hat{K}$ ($\times 10^3$ MT)	R^2	d
YELLOWFIN	4.8188 (21.21)*	0.0513 (8.30)	1.372	1.2883	351.2244	0.852	2.07
SKIPJACK	3.2853 (16.15)	0.0260 (5.57)	1.240	1.5686	264.9435	0.721	2.08
BIGEYE	1.0266 (15.86)	0.0114 (8.13)	2.110	1.9018	48.6540	0.846	1.94

*Values in parentheses below estimates of α and β are t-ratios.

TABLE 5: MSY, BIOECONOMIC, AND OPEN ACCESS EQUILIBRIA FOR YELLOWFIN IN THE ETA

Yellowfin Parameters: p = \$1300, $q = 1.372 \times 10^{-2}$, r = 1.2883, K = 351.2244
Maximum Sustainable: $X_{MSY} = 175.56$, $Y_{MSY} = 133.12$, $E_{MSY} = 46.9495$

	δ	c = \$2,000	c = \$2,500	c = \$3,000	c = \$3,500
BIOECONOMIC EQUILIBRIA	0.00	X* = 231.68 Y* = 101.59 E* = 31.96	X* = 245.70 Y* = 95.10 E* = 28.21	X* = 259.71 Y* = 87.18 E* = 24.47	X* = 273.73 Y* = 77.81 E* = 20.72
	0.05	X* = 228.21 Y* = 102.97 E* = 32.89	X* = 242.81 Y* = 96.56 E* = 28.98	X* = 257.35 Y* = 88.61 E* = 25.10	X* = 271.83 Y* = 79.16 E* = 21.23
	0.10	X* = 224.85 Y* = 104.23 E* = 33.79	X* = 240.02 Y* = 97.90 E* = 29.73	X* = 255.07 Y* = 89.96 E* = 25.71	X* = 270.00 Y* = 80.44 E* = 21.71
	0.15	X* = 221.58 Y* = 105.37 E* = 34.66	X* = 237.32 Y* = 99.15 E* = 30.45	X* = 252.87 Y* = 91.23 E* = 26.30	X* = 268.24 Y* = 81.65 E* = 22.19
	0.20	X* = 218.41 Y* = 106.40 E* = 35.51	X* = 234.71 Y* = 100.31 E* = 31.15	X* = 250.74 Y* = 92.42 E* = 26.87	X* = 266.54 Y* = 82.80 E* = 22.64
OPEN ACCESS	$\delta \to \infty$	X_∞ = 112.13 Y_∞ = 98.34 E_∞ = 63.92	X_∞ = 140.17 Y_∞ = 108.51 E_∞ = 56.43	X_∞ = 168.20 Y_∞ = 112.92 E_∞ = 48.93	X_∞ = 196.23 Y_∞ = 111.56 E_∞ = 41.44

TABLE 6: MSY, BIOECONOMIC, AND OPEN ACCESS EQUILIBRIA FOR SKIPJACK IN THE ETA

Skipjack Parameters: p = \$1200, $q = 1.240 \times 10^{-2}$, r = 1.5686, K = 264.9435
Maximum Sustainable: X_{MSY} = 132.4718, Y_{MSY} = 103.9005, E_{MSY} = 63.2518

	δ	c = \$2,000	c = \$2,500	c = \$3,000	c = \$3,500
BIOECONOMIC EQUILIBRIA	0.00	X* = 199.68 Y* = 77.16 E* = 31.16	X* = 216.48 Y* = 62.12 E* = 23.14	X* = 233.28 Y* = 43.73 E* = 15.12	X* = 250.08 Y* = 22.01 E* = 7.10
	0.05	X* = 198.32 Y* = 78.23 E* = 31.81	X* = 215.55 Y* = 63.04 E* = 23.59	X* = 232.71 Y* = 44.41 E* = 15.39	X* = 249.83 Y* = 22.35 E* = 7.22
	0.10	X* = 196.99 Y* = 79.25 E* = 32.44	X* = 214.64 Y* = 63.92 E* = 24.02	X* = 232.17 Y* = 45.05 E* = 15.65	X* = 249.59 Y* = 22.68 E* = 7.33
	0.15	X* = 195.71 Y* = 80.22 E* = 33.06	X* = 213.77 Y* = 64.77 E* = 24.44	X* = 231.64 Y* = 45.68 E* = 15.90	X* = 249.36 Y* = 23.01 E* = 7.44
	0.20	X* = 194.46 Y* = 81.15 E* = 33.65	X* = 212.91 Y* = 65.59 E* = 24.84	X* = 231.12 Y* = 46.28 E* = 16.15	X* = 249.13 Y* = 23.32 E* = 7.55
OPEN ACCESS	$\delta \to \infty$	X_∞ = 134.40 Y_∞ = 103.88 E_∞ = 62.33	X_∞ = 168.01 Y_∞ = 96.42 E_∞ = 46.28	X_∞ = 201.61 Y_∞ = 75.59 E_∞ = 30.24	X_∞ = 235.22 Y_∞ = 41.40 E_∞ = 14.19

TABLE 7: MSY, BIOECONOMIC, AND OPEN ACCESS EQUILIBRIA FOR BIGEYE IN THE ETA

Bigeye Parameters: $p = \$1300$, $q = 2.11 \times 10^{-2}$, $r = 1.9018$, $K = 48.6540$
Maximum Sustainable: $X_{MSY} = 24.3270$, $Y_{MSY} = 23.1332$, $E_{MSY} = 45.0667$

	δ	c = $400	c = $500	c = $600	c = $700
BIOECONOMIC EQUILIBRIA	0.00	$X^* = 31.62$ $Y^* = 21.05$ $E^* = 31.56$	$X^* = 33.44$ $Y^* = 19.86$ $E^* = 28.18$	$X^* = 35.26$ $Y^* = 18.46$ $E^* = 24.80$	$X^* = 37.09$ $Y^* = 16.77$ $E^* = 21.43$
	0.05	$X^* = 31.28$ $Y^* = 21.24$ $E^* = 32.19$	$X^* = 33.15$ $Y^* = 20.09$ $E^* = 28.72$	$X^* = 35.02$ $Y^* = 18.66$ $E^* = 25.25$	$X^* = 36.89$ $Y^* = 16.96$ $E^* = 21.79$
	0.10	$X^* = 30.94$ $Y^* = 21.42$ $E^* = 32.81$	$X^* = 32.87$ $Y^* = 20.28$ $E^* = 29.24$	$X^* = 34.79$ $Y^* = 18.85$ $E^* = 25.69$	$X^* = 36.70$ $Y^* = 17.15$ $E^* = 22.15$
	0.15	$X^* = 30.61$ $Y^* = 21.59$ $E^* = 33.42$	$X^* = 32.60$ $Y^* = 20.46$ $E^* = 29.75$	$X^* = 34.56$ $Y^* = 19.04$ $E^* = 26.11$	$X^* = 36.51$ $Y^* = 17.33$ $E^* = 22.50$
	0.20	$X^* = 30.29$ $Y^* = 21.74$ $E^* = 34.02$	$X^* = 32.33$ $Y^* = 20.63$ $E^* = 30.25$	$X^* = 34.34$ $Y^* = 19.22$ $E^* = 26.53$	$X^* = 36.33$ $Y^* = 17.51$ $E^* = 22.83$
OPEN ACCESS	$\delta \to \infty$	$X_\infty = 14.58$ $Y_\infty = 19.42$ $E_\infty = 63.12$	$X_\infty = 18.23$ $Y_\infty = 21.68$ $E_\infty = 56.36$	$X_\infty = 21.87$ $Y_\infty = 22.90$ $E_\infty = 49.61$	$X_\infty = 25.52$ $Y_\infty = 23.08$ $E_\infty = 42.86$

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