AN ECONOMIC ANALYSIS OF A POTENTIAL OVERFISHING PROBLEM: THE N.C. HARD CLAM FISHERY

Yu-Mong Hsiao*
Thomas Johnson**
J.E. Easley, Jr.**

*Assistant Professor of Economics, Campbell University

**Professors, Department of Economics and Business, North Carolina State University

Sea Grant Technical Report No. UNC-SG-86-11
UNC Sea Grant College Program
N.C. State University

November 1986

$3.50

ABSTRACT

The recent increase in landings in the North Carolina hard clam fishery has triggered concern of potential overfishing. The overfishing problem is investigated in this study by contrasting the historical data and the empirical supply curve with the long run steady-state supply curve. The steady-state supply curve is derived from intertemporal maximization of social welfare subject to population dynamics. The empirical supply curve is estimated using a simultaneous equation model.

The model components of the steady-state supply curve are estimated. The results show that the North Carolina hard clam fishery exhibits decreasing returns to scale with respect to resource stock. The maximum sustainable yield is not significantly different from two million pounds of meat per annum. Historical records show that the suspected biological overfishing has not been serious yet. But economic overfishing has occurred in the past and has reached serious levels in recent years. Since these results are based on the mean value estimated from the past 20 years' catch-effort data, the maximum sustainable yield may be underestimated, and the economic overfishing statement may be too conservative.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

The authors appreciate the financial assistance for this project from the UNC Sea Grant College Program Grant Number NA 38AA-D-00012. Special thanks are extended to the members of the National Marine Fisheries Service who provided helpful information and essential data through personal interviews and correspondences. We also thank Charles Peterson of the UNC Institute of Marine Science and Fentress "Red" Munden of the N. C. Division of Marine Fisheries for their valuable input. Helpful reviews of an earlier draft were provided by Wade Griffin of Texas A & M, Dennis Spitsbergen of DMF, and Charles Peterson.

AN ECONOMIC ANALYSIS OF A POTENTIAL OVERFISHING PROBLEM: THE N.C. HARD CLAM FISHERY

I. INTRODUCTION

The Hard Clam Resource in North Carolina

Hard clams, *Mercenaria mercenaria*, are found in nearly all of the sheltered marine waters of North Carolina, but the commercial fishery is centered principally in Carteret and Brunswick counties. Smaller quantities are caught in New Hanover, Dare, Hyde, Onslow and Pender counties (Tiller, Glude and Stringer 1952, Maiolo and Tschetter 1983).

The clam fishery in North Carolina has grown sharply and now ranks among the state's most valuable fisheries (Maiolo and Tschetter 1983). Dockside value in 1982 was more than 25 times the value recorded in 1976, contributing approximately one-fifth of the total value received from shellfish in North Carolina (Table 1). In addition, hard clam landings in pounds of meat jumped from a negligible position before 1976, to third place in 1978 and 1979. These landings surpassed landings in Massachusetts, New Jersey and Virginia -- three of the five traditional, leading states of the hard clam fishery in the United States.

The geometrical growth in value and landings is presumably attributed to high demand, especially in Northern areas where local harvests were reduced because of extremely cold weather. With high prices for clams being offered, N. C. landings increased. The increase resulted from the use of more sophisticated mechanical harvesting gear (hydraulic escalator dredges and clam kickings) and a larger number of fishermen. Many worked part-time, using rakes whenever weather permitted. Landings by gear are shown in Table 2.

The booming phenomenon of the clam fishery triggered concern of potential overfishing, and of potential negative effects from clamming operations on other fisheries, notably the bay scallop fishery (Street 1981, 1982, 1983).

TABLE 1

VALUE RECEIVED BY NORTH CAROLINA FISHERMEN 1976-1982

(in current dollars)

Year	Hard Clam	Total Shellfish	Total Fish & Shellfish	Share of Hard Clam in: Shellfish	Grand Total
		(current dollars)		(Percent)	
1976	258,163	12,796,018	27,409,286	2.02	.94
1977	1,068,880	12,295,207	28,584,435	8.69	3.74
1978	2,449,054	13,591,421	40,608,865	18.02	6.03
1979	4,473,737	25,624,765	58,454,086	17.46	7.65
1980	5,554,047	34,057,756	68,783,510	16.31	8.07
1981	5,386,803	21,239,682	57,520,010	25.36	9.37
1982	6,606,132	31,849,411	63,823,852	20.74	10.35

Source: Current Fisheries Statistics: North Carolina Landings, Annual Summary (U.S. Department of Commerce 1976-1979); North Carolina Landings (N.C. Department of Natural Resources and Community Development 1980-1982).

A forthcoming paper examines these potential negative effects (Hsiao, Easley, Johnson, forthcoming).

The Overfishing Problem.

With increased harvesting pressure evident, fisheries management authorities suspect that the clam fishery may have hit its peak. And despite continued efforts to preserve the fishery, it will probably decline unless proper management policy is implemented.

The hard clam fishery in North Carolina is essentially an open-access resource (or "common property resource" as it is often inaccurately called, see Clark 1976, p. 6) with the exception of a small number of private leases.[1] It is regulated by the N. C. Division of Marine Fisheries. Regulations specify seasons, cull tolerances and practices, harvest limits, harvest areas, times and gear. According to an interview with a service officer (Mr. Munden), hand gear (e.g., rake) is allowed year-round Monday through Saturday. Clam kicking (or otter trawl) is allowed December through March, Monday through Wednesday. And the hydraulic escalator dredge is traditionally operated during the winter daylight hours, Monday through Friday. All types of gear require a local license. There are also landing tax and annual fees for dealers and processors, but all of these fees and taxes are fairly low[2] (Street 1976, Maiolo and Tschetter 1983).

---

[1]Currently, there are 311 shellfish leases covering about 3,000 acres. The filing fee is $25, and the rental per acre per year is $5 (Street 1976, Maiolo and Tschetter 1983).

[2]The license fee for each person is $1 per year. For boats up to 18 feet, $3. Boats 18'-26' -- 50 cents per foot; 26' plus at 75 cents per foot. An annual fee for shucker-packers is $25; for shellstock-shippers, $10. The landings tax for dealers is 6 cents per bushel. The license fees for boats are currently revised effective January 1, 1984, as follows: boats up to 18 feet at $1 per foot; 18'-38' at $1.50 per foot; and 38' plus at $3 per foot.

TABLE 2

HARD CLAM LANDINGS BY GEAR IN NORTH CAROLINA 1960-1982
in pounds of meats (Percentage of total clam landings)

Year	Rakes	Clam Dredge	Otter Trawl	Others
1960	207500(48.09)	224000(51.91)	-	-
1961	261400(53.30)	229000(46.70)	-	-
1962	186200(75.48)	60500(24.52)	-	-
1963	258800(78.02)	67900(20.47)	-	5000(1.51)
1964	212400(83.16)	40000(15.66)	-	3000(1.17)
1965	283400(90.57)	28000(8.95)	-	1500(.48)
1966	183500(78.82)	-	-	49300(21.18)
1967	139000(69.43)	1700(.85)	-	51600(25.78)
1968	86700(42.58)	50200(24.66)	-	66700(32.76)
1969	60800(24.10)	134700(53.39)	-	56800(22.51)
1970	90300(32.03)	141400(50.16)	-	50200(17.80)
1971	74100(29.25)	143700(56.73)	10900 (4.30)	24600(9.71)
1972	99500(36.42)	91200(33.38)	75400(27.60)	7100(2.60)
1973	58900(15.53)	187100(49.33)	126400(33.32)	6900(1.82)
1974	56100(19.51)	189400(65.86)	42100(14.64)	-
1975	47600(16.70)	223800(78.53)	10600(3.72)	300(1.05)
1976	24000(7.83)	267500(87.30)	8100(2.64)	6800(2.22)
1977	79300(10.72)	114300(15.46)	545800(73.82)	-
1978	259104(29.04)	108567(12.17)	367990(41.24)	156574(17.55)
1979	1009300(69.62)	61600(4.25)	328900(22.69)	49900(3.44)
1980	928827(60.25)	55773(3.62)	492097(31.92)	65022(4.22)
1981	938236(64.34)	141959(9.74)	292440(20.05)	85561(5.87)
1982	1136360(66.77)	107674(6.33)	396953(23.33)	60806(3.57)

Source: Current Fisheries Statistics: North Carolina Landings, Annual Summary (U.S. Department of Commerce 1960-1979); N.C. Department of Natural Resources and Community Development 1980-1982 unpublished data.

The hydraulic escalator dredge requires an additional permit from the Marine Fisheries director. The special permit is required for reporting purposes and is free (Street 1976).

The distinguishing characteristics of a common property resource have important implications. The ownership of, or property rights to, the resource are not clearly defined. Therefore no single user has exclusive property rights to these resource stocks, nor can the user prevent others from sharing in the exploitation of the resource. Efforts by one user to conserve the resource will be futile, since there is no guarantee that others will do the same. Consequently, the stock is depleted rapidly until further extraction is not economical. Economic and biological overfishing[3] follow (Lewis 1975, Altobello 1976, Waters 1982).

Models in Fishery Management - An Overview.

Current fishery management is often cast as a problem in dynamic optimization where the management's objective may be to maximize the present value of net benefits. This maximization is subject to adjustments in the stock resulting from growth, natural mortality and man's harvesting activities (Crutchfield and Zellner 1962, Plourde 1970

[3]Biological overfishing is generally referred to here as concern about the possibility of declining catch in the future. There are two types of biological overfishing in the literature. One is the phenomenon of "recruitment overfishing" in which the population is maintained at a level below that of optimal production (usually referred to as the maximum sustainable yield) and is recognized in the lumped parameter biological model, or biomass model. On the other hand "growth overfishing," in which fish are caught at an age younger than some optimal age, is recognized in the multi-cohort modal (Reed 1980). In contrast to biological overfishing the phenomenon of "economic overfishing" refers to fishing effort in an open-access fishery in excess of optimal fishing effort (i.e., that which maximizes the economic rent).

and 1971, Quirk and Smith 1970, Clark 1973, Brown 1974, Neher 1974 and Spence 1973). These resource models are called bioeconomic models. Theory and methods to solve the dynamic optimization problems that emerge from a bioeconomic model have focused almost exclusively on lumped parameter models where the resource in question is defined by a single-state variable called biomass, as pounds of meat of fish, for example, or cubic board feet of timber. Biomass models usually have the advantages of simplicity and mathematical tractability. But these models do not take into account age-dependent attributes of the resource stock or externalities that arise from biological or economic interdependence between different fisheries (Conrad 1981).

Age-dependent problems are generally solved by application of a multiple cohort model. Problems between two or more species are examined with multiple-species models (Conrad 1981, Clark 1976). A multiple cohort model has been applied to the hard clam resource in Great South Bay, Long Island, New York (Conrad 1981, 1982). Similar models have been developed for Arctic-Norwegian cod by Reed (1980) and for red deer (Cevus Elaphusl) by Beddington and Taylor (1973). Waters (1983), Conrad and Castro (1983), Edwards (1983), Wilson (1982), Lampe (1976), Lewis (1975) and Anderson (1975) provide examples of multiple-species management models.

As the management problem of interest involves both multi-species and multi-cohort types of problems, it would be ideal to integrate both the multiple-species management model and multiple cohort model into a comprehensive management model to solve all relevant economic problems at once. But the data required for this ideal model is tremendous and currently unavailable. Under these circumstances, this study proceeds to model the overfishing and externalities problems separately. It is believed that isolating the harvest conflict problem from the hard clam fishery model would not have a significant effect on the overall optimal solution because negative externalities can be resolved to some extent by optimally controlling the hard clam harvest rate and by regulation.[4]

The overfishing problem is approached with a biomass model (single-state or total biomass) instead of a multiple cohort model because of a lack of data. Parameters of survival rates of hard clams for North Carolina are available by size (length), but not by age class (Peterson 1982, Beal 1983). Other parameters such as age-dependent fecundity rates, age distribution and carrying capacity required for applying a multi-cohort model are unavailable. The problem is approached with a biomass model for simplicity since the historical data on North Carolina hard clam landings are maintained in the aggregate measures, total pounds of meat and total dollar value.

Smith (1980) suggests a stochastic resource regeneration model for the U.S. northern lobster fishery in which the biomass growth function and technical production function (or extraction function) are estimated in one equation. This model requires only annual landings and aggregate fishing effort data. Smith's framework can be applied to the North Carolina hard clam fishery. Fishing effort data is not available, but can be estimated from license records by gear type and

---

[4]Example of reducing a negative effect on oyster beds by regulation can be found in Street's 1976 comprehensive report, section 2.3.1.2.1.3.

its relative productivity. The overfishing problem in the clam fishery can be explored to some extent with the estimated biomass results under the limited available information constraint.

Objective.

The objectives of the study are to investigate the current management problems in the North Carolina hard clam fishery and to develop a corresponding resource management model from which the optimal harvest policy can be determined. The objectives are as follows:

1. To develop a (biomass) theoretical model and derive a long-run (steady-state) optimally controlled supply curve of North Carolina hard clams;
2. To specify and estimate model components;
3. To develop an empirical model that estimates the demand for and supply of the North Carolina hard clam, and to conduct economic analysis on the North Carolina hard clam market at the ex-vessel level;
4. To identify the biological maximum sustainable yield and overfishing pressure by contrasting the empirical supply curve to the optimally controlled supply curve;
5. To outline suggestions for further research.

II. STEADY-STATE OPTIMALLY CONTROLLED SUPPLY CURVE

In the area of natural resource management, the "steady-state" refers to the characteristics of a natural resource system when production/extraction rates are limited to the flow component of the system and natural resource stocks remain unchanged through time. In the relevant literature for this class of problems, analyses of natural resource systems under steady-state conditions may be dichotomized as follows: those in which steady-state conditions are derived from the dynamic structure of optimal intertemporal production paths (see, for example, Conrad 1981, 1982; Brown 1974; Beddington et al. 1975; Plourde 1971; Quirk and Smith 1970; Clark 1974 and Burt and Cummings 1970); and those in which a static framework is used, and the steady-state conditions simply posited (Bradley 1970; Smith 1968, 1969 and 1974). Several earlier writers such as Gordon (1954) and Turvey (1964) also used a static framework but did not explicitly introduce a mathematical optimization model into the analysis (Burt and Cummings 1977).

The difference in the structure of the steady-state conditions deduced from these two approaches is the introduction of the discount rate. The static framework excludes the discount rate, resulting in a set of potentially misleading implications in terms of public policy. For example, referring to Figure 1, Bradley (1979, p. 39) argues that under steady-state conditions the optimal fish stock must lie between points c and d (where c corresponds to "maximum sustainable physical yield"). This argument is also given by Smith (1968, p. 427; 1969, p. 191). When the discount rate is introduced, it can be shown that the optimal steady-state fish population may lie at any point between b and d (Burt and Cummings 1977, p. 2; Clark 1973, 1976). (See following discussion of first order conditions for an explanation of this result).

Because of the introduction of the discount rate, a long-run equilibrium supply equation derived from the dynamic framework of steady-state conditions is also referred to as a discounted supply curve (Clark 1976). In this chapter, a single-state biomass model is employed to derive the discounted supply curve. The theoretical framework[5] for a steady-state supply equation derived from optimal control theory and the policy implications of steady-state conditions are presented in the next section.

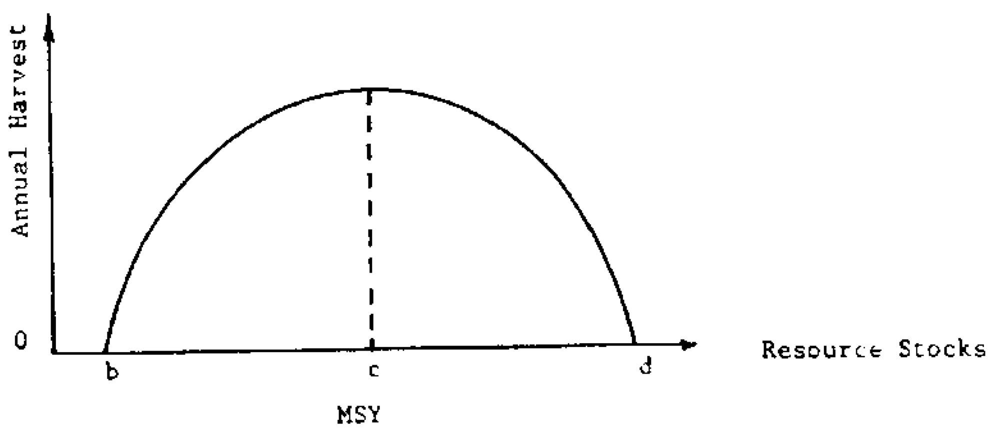

Figure 1: Steady-State Harvest Level versus Resource Stocks

Model components required for the application of the general model to the North Carolina clam fishery are discussed below. The estimation

---

[5]The basic framework of this section has been drawn partly from Clark (1976, pp. 159-172).

procedure and results of these model components are presented in the next chapter.

Theoretical Framework for the Steady-State Supply Equation.

Assume that the fishery resource is managed by an authority whose objective is to maximize the present value of social welfare from exploiting the resource over an infinite planning horizon.[6] Social welfare at each period t is defined as the difference between total social utility of fish consumption and total harvest cost. In notation, let P(Q) denote the inverse demand function for the given fishery resource harvested at rate Q, and $U(Q)=\int_0^Q P(q)dq$ represent the total social utility of fish consumption. Total harvest cost, depending on the resource stock (X) available and the harvest rate (Q), is given by the cost function C(X,Q). Then the social welfare at each period is represented by U(Q)-C(X,Q).[7] To prevent the pulse fishing problem, it is assumed that marginal cost with respect to the harvest rate, Q, is nondecreasing (for details, see Clark 1976, p. 172):

$$C_Q(\cdot) = MC_Q = \frac{\partial C(\cdot)}{\partial Q} > 0; \quad C_{QQ}(\cdot) = \frac{\partial^2 C(\cdot)}{\partial Q^2} \geq 0.$$

---

[6]Another alternative commonly used is to maximize the present value of net economic profits accruing from the fishery (for example, Waters 1983; Conrad 1981 and 1982; Crutchfield and Zellner 1962; Altobello 1976). Most earlier works examining management issues are from the biological point of view and their objectives of the management models are usually to maximize the physical sustainable yield (Clark 1976).

[7]Social welfare defined in this study is equivalent to the sum of consumers' and producers' surplus.

In addition, larger fish stocks can be expected to reduce the fishing effort required for a given harvest rate (Q), resulting in a lower total cost. The first derivative of C(X,Q) with respect to X, denoted as $C_X(X,Q)$, will be negative.

Suppose δ is the rate of discount.[8] The objective of the fishery authority is then to choose the socially optimal fishery management policy to maximize the intertemporal social welfare functional of the form:

$$J(Q) = \int_0^{\infty} e^{-\delta t}(U(Q)-C(X,Q))dt \qquad (1)$$

The intertemporal maximization problem is subject to the population dynamics (state transition equation)

$$\frac{dX}{dt} = F(X)-Q(t),\ X(0) = X_0 > 0, \qquad (2)$$

and to the non-negative constraints,

$$X(t) \geq 0,\ Q(t) \geq 0, \qquad (3)$$

where X(t) denotes the resource stock (biomass) in period t. The function F(X) reflects factors affecting net growth of the resource and environmental carrying capacity. The instantaneous rate of change in the stock, $\frac{dX}{dt}$, is the difference between net growth of the resource F(X) and the fishing mortality rate Q(t).

---

[8]The discount rate may be thought of as the opportunity cost of investment or capital funds. It is the return that could be earned on a dollar invested <u>elsewhere</u> in the economy (Conrad 1981). Further discussions of an appropriate social rate of discount can be found in Lewis (1976).

In summary, the optimization problem is formulated as:

Maximize with respect to $Q(t)$ $\qquad J(Q) = \int_0^\infty e^{-\delta t}(U(Q)-C(X,Q))dt$

Subject to

$$\frac{dX}{dt} = F(X)-Q(t)$$

$$X(0)=Xo > 0$$

$$X(t) \geq 0$$

$$Q(t) \geq 0$$

The Hamiltonian Function.

To help perform the maximization, the Hamiltonian function is formulated as:

$$H(Q,X,\lambda) = e^{-\delta t}(U(Q)-C(X,Q))+\lambda(t)(F(X)-Q(t))$$

In the framework of optimal control theory, Q corresponds to the control or decision variable, X, the state variable, and λ is a multiplier (or shadow price) representing the imputed demand price of the unharvested resource in terms of present consumption foregone.

The First Order Condition and the Steady-State Supply Equation.

If the control constraint $Q \geq 0$ is not binding, the maximum principle implies that optimization requires

$$\frac{\partial H}{\partial Q} = e^{-\delta t}(U'(Q)-C_Q(X,Q))-\lambda(t)=0$$

where $U'(Q)=\dfrac{dU(Q)}{dQ}$, so that along any optimal trajectory,

$$\lambda(t) = e^{-\delta t}(U'(Q)-C_Q(X,Q)) \qquad (4)$$

Hence, this necessary condition implies

$$\frac{d\lambda}{dt} = -\delta e^{-\delta t}(U'(Q)-C_Q(X,Q))+e^{-\delta t}(U''(Q)\frac{dQ}{dt} -C_{QQ}\frac{dQ}{dt} -C_{QX}\frac{dX}{dt})$$

$$= e^{-\delta t}(-\delta(U'(Q)-C_Q(X,Q))+U''(Q)\frac{dQ}{dt} -C_{QQ}\frac{dQ}{dt} -C_{QX}\frac{dX}{dt})$$

where $U''(Q) = \frac{d^2U(Q)}{dQ^2}$, $C_{QX}(\cdot) = \frac{\partial^2 C(X,Q)}{\partial_X \partial_Q}$.

On the other hand, the adjoint equation is

$$\frac{d\lambda}{dt} = -\frac{\partial_H}{\partial_X} = -(e^{-\delta t}(-C_X(X,Q))+\lambda(t)F'(X))$$

$$= e^{-\delta t}C_X(X,Q)-e^{-\delta t}(U'(Q)-C_Q(X,Q))F'(X)$$

where $F'(X)= \frac{dF(X)}{dX}$.

Equating these two expressions, we obtain

$$\frac{dQ}{dt} =[(\delta-F')\cdot(U'-C_Q)+C_{QX}\cdot(F-Q)+C_X]/(U''-C_{QQ}) \qquad (5)$$

for the optimal harvest rate Q(t).

According to the maximum principle, any optimal trajectory (X(t),Q(t)) must satisfy the nonlinear autonomous system of differential equations (eq. (2) and eq. (5)).

In steady-state, where $\frac{dX}{dt}=0$ and $\frac{dQ}{dt}=0$, from equations (2) and (5), we obtain

$$F'(X) - \frac{C_X(X,Q)}{U'(Q)-C_Q(X,Q)} = \delta \qquad (6)$$

or

$$F'(X) - \frac{C_X(X,Q)}{P(Q)-C_Q(X,Q)} = \delta \qquad (7)$$

where in steady-state $Q=F(X)$; $U'(Q)=P(Q)$. (8)

Equation (6) or (7) implies the optimal steady-state level of stock X and the optimal steady-state harvest rate, Q. To achieve this optimal steady-state stock, the rule requires that the sum of the marginal contribution to the growth rate plus cost savings due to the stock effect equals the discount rate. So in the steady-state, the stock is maintained to provide returns to the fishery (in the form of growth and cost savings) that are precisely equal to the rate of return obtainable on other capital assets elsewhere in the economy, (equal to δ).

When harvesting costs are independent of the population level (i.e., when $C_X(X,Q)=0$), equation (7) is reduced to $F'(X)=\delta$. This is identical to the basic equilibrium rule in capital theory.[9] In this case, as long as the discount rate is positive, the optimal steady-state of stock, denoted X_δ, is always less than the maximum sustainable yield level of stock, X_{msy}. Note that as the discount rate approaches zero, the optimal stock approaches the maximum sustainable yield level of stock. Figure 2(a) illustrates the growth function and the

[9]The basic equilibrium rule in capital theory requires that the marginal productivity of capital, $F'(X)$, equals the social time-preference rate, δ.

determination of the optimal steady-state stock, X_δ. Figure 2(b) shows the corresponding marginal growth rate, $F'(X)$, discount rate, δ, and the optimal level of stock, X_δ.

Referring to Figure 1, in the case of no stock effect, the optimal steady-state resource stock lies between points b and c. However, in the presence of stock effect (i.e., $C_X(X,Q)<0$), the optimal steady-state level of stock, denoted X^*, may lie at any point between b and d. As the marginal value of population (i.e., the net value of a unit of harvested fish) $P(Q)-C_Q(X,Q)$ is positive, the term $C_X(X,Q)/(P(Q)-C_Q(X,Q))$ is negative. Therefore the stock effect serves to reduce the effective value of the discount rate. Define

$$\delta^*=\delta - \frac{C_X(X,Q)}{P(Q)-C_Q(X,Q)} \quad .$$

The value of δ^* represents the effective discount rate. Figure 3 illustrates the determination of optimal steady-state level of stock, X^*, in the presence of a stock effect.

On the one hand, as shown in Figure 3, if the stock effect is so large that it results in a negative effective discount rate, e.g., δ^*_2, then the optimal steady-state level of stock is greater than the maximum sustainable yield level. In Figure 1, this implies that the optimal stock level lies between c and d. In practice this stock effect is often quite significant in many fisheries (see examples discussed in Chapter two, Clark (1976)).

On the other hand, if the stock effect is small such that the effective discount rate is positive, e.g., δ^*_1, then the optimal stock

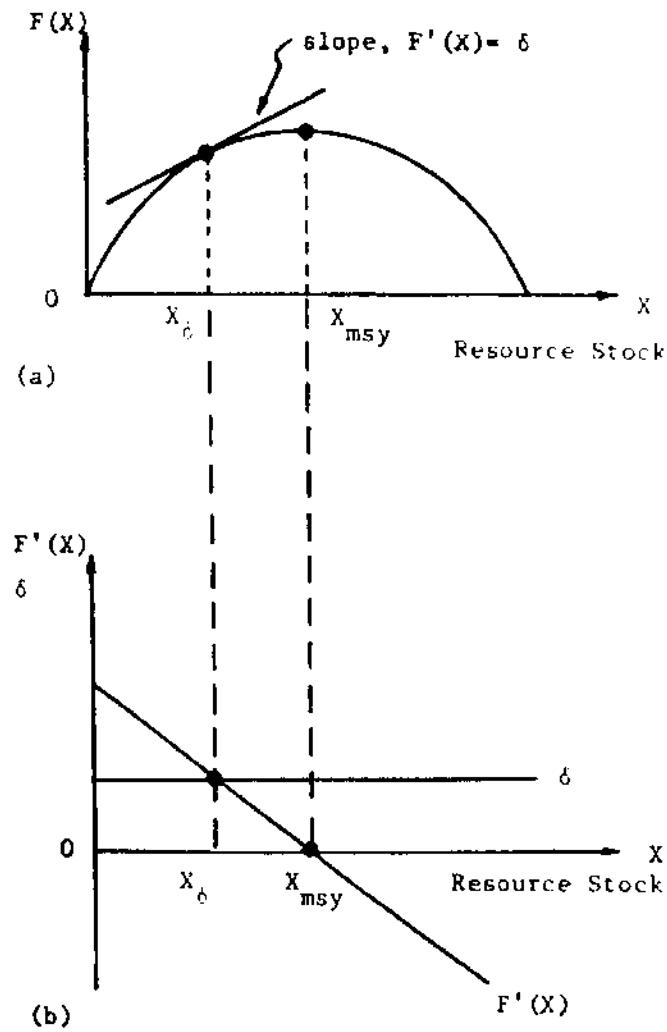

Figure 2 : The Determination of Optimal Steady State Level of Stock When $C_x(X,Q)=0$, (No Stock Effect).

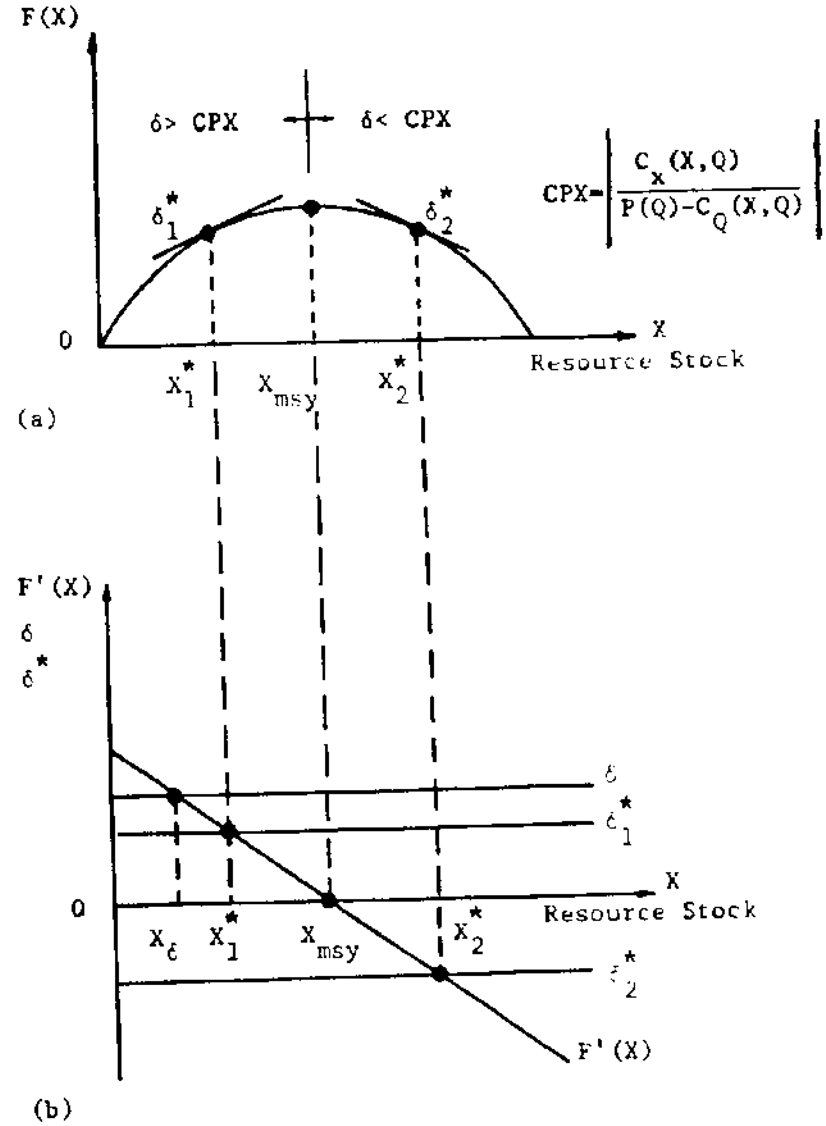

Figure 3 : The Determination of Optimal Steady State Level of Stock in the Presence of Stock Effect, $C_x(X,Q)<0$.

level, X*, will be maintained below the maximum sustainable yield level. This implies that X* lies between b and c in Figure 1.

In summary, as long as the stock contributes to cost savings, it is worthwhile to preserve the resource stock for future exploitation. Therefore the optimal stock level with the stock effect, X*, is always greater than that without the stock effect, X_δ.

Equation (7) can be solved for the price P(Q), or,

$$P(Q) = H_\delta(X) - C_Q(X,Q) - \frac{C_X(X,Q)}{\delta - F'(X)}. \tag{9}$$

The corresponding optimal sustainable yield is given by,

$$Q = F(X) \tag{10}$$

Equations (9) and (10) comprise a two-equation system that identifies the optimal sustainable Q and X. Solving for X in terms of Q from equation (10) and then substituting the result into (9), we obtain a functional relationship between P and Q.[10] This result is the steady-state (equilibrium) supply curve for the optimally controlled fishery, or the discounted supply curve as referred to by Clark (1976).

---

[10] From equation (10) $X = F^{-1}(Q)$; substituting this result, equation (9) becomes

$$P(Q) = H_\delta(F^{-1}(Q)) - C_Q(F^{-1}(Q),Q) - \frac{C_X(F^{-1}(Q),Q)}{\delta - F'(F^{-1}(Q))}$$
$$= \phi(Q)$$

Steady-State Conditions and Policy Implications.

Information regarding the steady-state conditions may provide valuable policy implications. The comparison of optimal steady-state harvest rates with observations of current catches provides a qualitative basis for judgments regarding the presence of an overfishing problem and the optimal direction of change that public policy may affect. Thus, a situation with optimal steady-state harvest rates less than current catches may imply the presence of overfishing and the desirability of policies to limit the entry. Alternatively, current catches less than the optimal steady-state harvest rate may imply the reverse.

In addition, the optimal steady-state multiplier (shadow price) and harvest rate also provide a quantitative basis for management policies regarding the optimal catch (or landings) tax and quota respectively. These policies will serve to guide an overfished resource to the optimal steady-state stock and maintains it indefinitely (Clark 1980, Conrad 1981, and Burt and Cummings 1977).

Model Components.

This section discusses the relevant biological and economic components of the model stated in the above section. The objective is to discuss the data available, the commonly used functional forms, and the specifications adopted in this study that the model applies to the North Carolina hard clam fishery. The biological processes of growth and mortality determine the rate at which the population biomass changes over time. There are two sources of mortality - natural mortality and man's harvesting (technical production or extraction).

The industry harvest rate is a function of fishing effort and the resource stocks available. Valuation of these harvests requires information about the costs of catching clams and the demand for North Carolina hard clams. The demand for North Carolina hard clams is discussed and estimated in Chapter Four.

The Population Growth Function.

In marine fishery literature, the most extensively used form of the population growth function is the logistic function. It was used by Graham (1935) to study North Sea trawling and by Schaefer (1954) fo Pacific tuna. Recent use of the logistic in the analysis of populatio dynamics includes work by Smith (1980) on the U.S. northern lobster an blue whale, Mayo and Miller (1976) on North Atlantic redfish, Pinhorn (1976) on North Atlantic groundfish in general and cod in particular, Pope (1976) on North Atlantic cod and redfish, Halliday and Doubleday (1976) on groundfish for the Scotian Shelf, Lett and Benjaminsen (1977) on Northwestern Atlantic harp seals, Allen (1976) on baleen whales, Lewis (1976) on Eastern Pacific yellowfin tuna, and Altobello (1976) on Atlantic sea scallop and recent assessments of whale populations (Anon. 1976).

A different model, the Beverton-Holt model, (Beverton and Holt 1957, Ricker 1973, Clark 1976) assumes a density-dependent relative mortality rate and has been used in the management of North Sea fisheries. The Ricker growth function has recently been employed in studies of Northeast Atlantic cod (Cushing 1973) and Northeast Arctic cod (Garrod and Jones 1974). Lett and Doubleday (1976) have shown that Pella-Tomlinson (1969) models give a better description of the extensive data on Gulf of St. Lawrence cod than does the logistic (May et al., 1978).

The logistic growth model implies continuous reproduction as opposed to seasonal breeding. In applying the model, one must assume that progeny age instantaneously to adulthood. Deriso (1980) proposes a delay-difference population model by incorporating a modified Brody weight equation and a flexible form of a spawner-recruit function. The modified Brody weight equation is employed to convert the age-structured population dynamics into a biomass-type model. The general spawner-recruit formulation for an exploited seasonal breeding population contains the Beverton-Holt and the Ricker models as special cases. The delay-difference model is used to estimate the biological parameters for the yellowtail flounder of New England, the Pacific halibut and the haddock of Georges Bank (Deriso 1980). In a recent study, the Deriso model was applied to the management of Atlantic menhaden fishery (Ruppert et al., 1981).

May et al., (1978) use eight commonly adopted population models[11] to examine their implications for equilibrium yield versus effort relations under environmental uncertainty. Despite the criticism of ignoring age-structure and time-delay effects on the reproduction process, May et al. conclude that the logistic, in contrast to seven alternatives, is neither overly optimistic nor overly pessimistic in messages that bring about the dynamics of harvested population under environmental uncertainty. In addition, May et al. present a caveat

---

[11]Eight models include the logistic and seven alternative functions collected from studies by Fox (1970), Beverton-Holt (1957), Chapman (1973), Doi (1973), Ricker (1973) and Pella-Tomlinson (1969).

that, incorporating the age-structure and time-delay effects into population growth models, introduces a high degree of density dependenc and nonlinearity in the net population growth rates that lead to overshoot and overcompensation. This results in population patterns o sustained oscillation or even apparently chaotic fluctuation. May et al. (1978, p. 241) cite examples in works by Beddington and Horwood et al. Other examples can be found in the models of Clark (1976).

Deriso's (1980) estimation results, derived from his delay-difference model, provide another example. There has been a tendency for fishing mortality to be underestimated and natural mortality to be overestimated in comparison to published values. The logistic growth model is adopted in this study since it is free of mathematical complications and fits catch-effort data for most stocks fairly well.

The Logistic Growth Function.

The usual form of the logistic equation (in the absence of extraction) is

$$\frac{dX}{dt} = F(X) = rX(t)(1-X(t)/K),$$

where X(t) is the resource biomass at time t, r and K are positive constants that are the population parameters. The parameter r is called the intrinsic growth rate and K is usually referred to as the environmental carrying capacity or saturation level.

In some studies[12] the logistic equation is written as

[12] For example, Smith (1980), Bell (1972), Lewis (1975), Altobello (1976), Plourde (1970), Quirk and Smith (1969).

$$\frac{dX}{dt} = mX(t) - nX(t)^2 \tag{11}$$

where m is the constant growth rate of the biomass, and nX(t) the variable natural death rate. As can be seen, m is equivalent to r and n equivalent to r/K. This study follows the notation of equation (11).

The logistic equation is a symmetric function with two equilibrium solutions at X(t)=0 and X(t)=m/n. The global asymptotically stable steady-state stock size, or carrying capacity, is given by $X^*=m/n$. The maximum sustainable yield stock size occurs at X=m/2n, with the corresponding maximum sustainable yield given by $MSY=m^2/4n$ (see Figure 4). Moreover, we have

$$0 < X < m/n \qquad \text{implies} \qquad \frac{dX}{dt} > 0.$$

whereas

$$X > m/n \qquad \text{implies} \qquad \frac{dX}{dt} < 0.$$

If X(t) were not equal to m/n initially, with no harvest it would approach m/n asymptotically as is shown in Figure 4 where time path (1) is an approach path from an initial X in excess of m/n, and time path (2) is an approach path from an initial X less than m/n (Clark 1976, Conrad 1981, Smith 1980).

In summary, differential equation (11) describes the change in the resource stock for a species not commercially exploited by man. Commercial exploitation requires a modification of equation (11) to account for man's harvesting activities. This modification is developed in the next section.

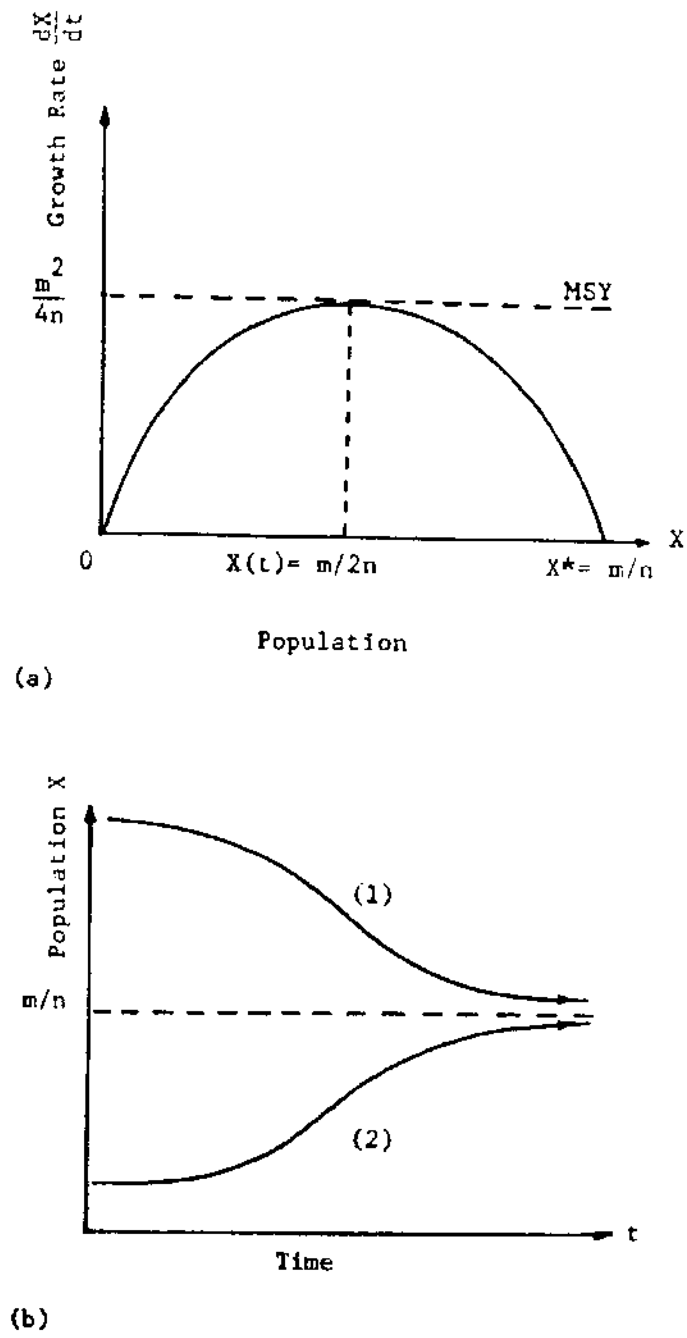

Figure 4 : The Logistic Equation: (a) The Logistic Growth Function $\frac{dX}{dt} = F(X) = mX(t) - nX(t)^2$ (b) Typical Solution Curves.

The (Technical) Production/Extraction Function.

A production function defines the maximum output obtainable from a given bundle of inputs. In a single species fishery, the output from commercial fishing would be catch or yield (or landings) denoted by Q(t). The bundle of man-made inputs utilized in catching fish are aggregated into a single input variable called "fishing effort" and denoted by E(t). Fishing effort is directed at the fish stock X(t) and results in a yield Q(t) according to Q(t)=H(E(t),X(t)) where H(E(t),X(t)) is the production function for the fishery.

The simplest and most extensively used form of the fishery production function is Q(t)=qE(t)X(t), where q is a positive constant and is called the catchability coefficient. This production function exhibits constant returns to scale (or unitary output elasticity) with respect to both fishing effort and fish stock. This functional form has been proposed and applied extensively to many fisheries by Schaefer (1957). The basic hypothesis underlying this model is that catch per unit effort, Q(t)/E(t), is proportional to the biomass level, and that this proportionality remains valid for all levels of E(t) and X(t). This hypothesis in turn is based on several additional assumptions, including:

1. Uniform distribution of the fish population
2. Nonsaturation of fishing gear
3. Noncongestion of fishing vessels

In considering gear saturation and fishing congestion problems, Clark (1976) proposes that the production function exhibit decreasing returns to scale. But he admits that the alternative is more or less based on an ad hoc formulation. In addition, throughout the theoretical and empirical resource literature there seems to be no agreement regarding the properties of the industry production (extraction) function. On one hand, Plourde (1971) has assumed that the production function is concave. Others, including Spence (1975), have assumed that the extraction function is characterized by increasing returns to scale. Dasgupta and Heal (1979) postulate that the extraction function exhibits decreasing returns to scale in fishing effort (E) and resource stock (X) at 'large' values of E, but it exhibits increasing returns at 'small' values of E.

While most biologists including Bell (1972) support the assumption of a unitary output elasticity of effort, Carlson et al. (1973) found that elasticity of effort was often not unitary for many fisheries when stock size was assumed fixed. Smith (1980) argues that with respect to the output elasticity of effort, the issue must be resolved empirically. The reason is that in the aggregate, crowding by fishermen, regulation of gear and/or an uneven and unknown distribution of the resource on the ocean bed may reasonably result in an average extraction function with an output elasticity less than unitary. A stochastic model applied to the northern lobster and blue whale fisheries suggests that output elasticity of effort is less than unity in lobstering, but not significantly different from unity in whaling.

The assumptions of the CPUE hypothesis are unlikely to hold true as a whole since the North Carolina clam fishery involves different productivities of gear type and wide-spread stocks among seven counties. This study shares Smith's viewpoints and extends the argument that both output elasticities of effort and stock must be resolved empirically. Thus a general Cobb-Douglas production function, i.e., $Q(t)=qE(t)^{\alpha}X(t)^{\beta}$, is assumed for the empirical study. The Cobb-Douglas formulation is capable of representing gear congestion (when $\alpha<1$) and saturation (when $\beta<1$). It also contains Schaefer's specification of the production function ($\alpha=1$ and $\beta=1$), and Smith's specification ($\beta=1$), as special cases.

The net growth function for a commercially exploited fishery (equation 11) is modified by subtracting fishing mortality, or Q(t). Given that the extraction function is a general Cobb-Douglas form, the equation (11) becomes:

$$\frac{dX}{dt} = mX(t)-nX(t)^2-qE(t)^{\alpha}X(t)^{\beta} \tag{12}$$

For the purpose of estimation from yearly data, equation (12) is modified to an equivalent discrete time model as follows:

$$X(t)-X(t-1)=mX(t-1)-nX(t-1)^2-qE(t-1)^{\alpha}X(t-1)^{\beta} \tag{13}$$

and

$$Q(t-1)=qE(t-1)^{\alpha}X(t-1)^{\beta} \;. \tag{14}$$

Using equation (13) to estimate directly the population parameters (m and n) and extraction parameters (q, α and β) requires a series of observations on X(t) and E(t). Annual values of fishing effort E(t) can be estimated using numbers of licenses by gear type. But observations on stock size X(t) cannot be found in any existing sources. Since annual landings Q(t) are readily available and given the assumption that the net growth function and extraction function hold true from year to year, the parameters (m, n, q, α and β) can be estimated with a single equation describing the recursive relationshi among Q(t), Q(t-1), E(t) and E(t-1) derived from equations (13) and (14).

Production/Extraction Costs.

The determination of a stock-dependent effort cost function in a fishery is usually approached in one of two ways. The first approach is to estimate the cost function directly. The second is to estimate the production function and then to derive the cost function based on the assumption of optimizing behavior on the part of the vessel owner/ operator (Conrad, 1981). The first approach requires cost information for vessel operation, harvest rates, and stock estimates through time. In practice, data regarding the cost information and stock estimates are not collected on a regular basis. To overcome this problem, Conra (1981) estimates unit costs (per bushel of harvest) from budget data and assumes a "stock effect" term[13] in modelling the hard clam resourc in Great South Bay. The latter approach requires a specification of the production function and a specification of a cost function relatin to fishing effort. The specification of the production function has been discussed in the previous section. Most studies assume that cost is proportional to fishing effort, e.g., Altobello (1976), Lewis

---

[13]Conrad assumed that the "stock effect" term took the form $(\ln(X(t)/Q(t)))^{-1}$. This form was assumed to capture the reduction in variable cost which would result when the starting stock X(t) increased relative to the amount harvested during the period, Q(t). When the sta stock to harvest ratio X(t)/Q(t) exceeds e=2.71828 the stock effect wil reduce average variable costs. For example, if the starting stock to harvest ratio were 10, variable costs could be reduced by about 57 perc

(1975), Waters (1983), Kellogg (1984), and Clark (1976). The second approach and the assumption that cost is proportional to fishing effort (i.e., $C(t)=cE(t)$) are employed in this study. Thus the cost function in terms of the resource stock $X(t)$ and harvest rate $Q(t)$ (corresponding to the Cobb-Douglas production function) is given as

$$C(X(t),\ Q(t))=c(q^{-1/\alpha}X(t)^{-\beta/\alpha}Q(t)^{1/\alpha})$$
$$= f(X(t))\cdot g(Q(t)),$$

since $Q(t)=qE(t)^{\alpha}X(t)^{\beta}$ and $E(t)=(Q(t)/qX(t)^{\beta})^{1/\alpha}$.

The cost coefficient, c, can then be estimated by regressing the total annual costs of operating various types of gear, against the aggregate fishing effort.

III. ESTIMATION OF MODEL COMPONENTS

The previous chapter described a framework for a steady-state supply equation and discussed the specifications of model components required for the application of the general model to the North Carolina clam fishery.

This chapter presents the estimation procedure and results for the population dynamics as shown in equations (13) and (14) and the cost function as discussed in the previous chapter.

Estimation of Population Dynamics.

For the purpose of estimation, equations (13) and (14) are reduced to a single equation in output and fishing effort. Dividing through equation (13) by X(t-1) yields

$$(X(t)/X(t-1))-1=m-nX(t-1)-qE(t-1)^{\alpha}X(t-1)^{\beta-1}\ . \qquad (15)$$

Next, equation (14) implies $X(t-1)=[Q(t-1)/(qE(t-1)^{\alpha})]^{1/\beta}$. Then equation (15) can be rewritten as

$$[Q(t)/Q(t-1)]^{1/\beta}[E(t-1)/E(t)]^{\alpha/\beta}-1$$

$$= m-n[Q(t-1)/qE(t-1)^{\alpha}]^{1/\beta}-qE(t-1)^{\alpha}[Q(t-1)/qE(t-1)^{\alpha}]^{(\beta-1)/\beta} \qquad (16)$$

This specification, with the assumption of an additive random disturbance term (which is normally distributed with mean zero and variance, σ^2), is consistent with Smith's (1980) stochastic resource regeneration model. Smith proves mathematically that as $\beta=1$, the steady-state distribution of the resource stock is a member of the Gamma family with the following moments:

$$E[x]=m/n-\sigma^2/2n$$

$$Var[x]=(2m-\sigma^2)\sigma^2/4n\ .$$

If the disturbance factor is not heavily weighted (or important), then the deterministic and stochastic specifications of the model will give similar results. That is, for small σ, the mean stochastic steady-state distribution is closely centered around the deterministic steady-state stock size, m/n. But when the disturbance term represents environmental uncertainty, and if σ is large, the mean steady-state stock size will be substantially smaller than the deterministic one. This follows since n is a fraction representing the natural death rate, and if σ^2 is large relative to 2n, then $E(X)=(m/n-\sigma^2/2n)$ will be substantially smaller than m/n.

Rearranging equation (16) yields

$$Q(t)/Q(t-1)=[1+m-n(Q(t-1)/qE(t-1)^{\alpha})^{1/\beta}$$

$$-\ qE(t-1)^{\alpha}(Q(t-1)/qE(t-1)^{\alpha})^{(\beta-1)/\beta}]^{\beta}(E(t)/E(t-1))^{\alpha} \quad (17)$$

Then, taking the natural logarithm, equation (17) becomes

$$y(t)=\ln Q(t)-\ln Q(t-1)$$

$$=\beta\ln[1+m-n(Q(t-1)/qE(t-1)^{\alpha})^{1/\beta}$$

$$-qE(t-1)^{\alpha}[Q(t-1)/qE(t-1)^{\alpha}]^{(\beta-1)/\beta}]$$

$$+\alpha[\ln E(t)-\ln E(t-1)] \ . \quad (18)$$

Assuming an additive disturbance term that is normally distributed with mean zero and variance σ^2, equation (18) is used in the nonlinear regression analysis to estimate the parameters m, n, α, β and q. This equation is estimated using the SAS NLIN Marquardt procedure. The convergence criterion was initially equal to 10^{-20}, but it was lowered to 10^{-12} because of the very slow convergence process.

Data.

Time-series data for the period 1956-81 are used in the regression analysis. But, in the absence of fishing effort data, an index of aggregate effort is constructed based upon information that is available. Estimates of relative productivities of the three basic gear types employed in clam harvesting (i.e., rakes and tongs, kicking and hydraulic escalator dredges) are combined with estimates of the number of working days for each gear type, and NMFS estimates of the number of units of each gear type. The clam fishing effort index is computed as:

$$E=\sum_{i=1} (\text{working days for gear type i})\cdot(\text{relative productivity})\cdot(\text{units of gear type i})\cdot(\text{percentage of fisherman who held gear type i licenses will work on a good working day})$$

During this period, seasons and the number of days fishing is allowed within a season were both regulated by gear type. Estimates of the number of days fishing is allowed are then modified by the estimates of the number of days fishing is effectively closed by bad weather (in consultation with N.C. Division of Marine Fisheries biologists). In addition to estimates of gear productivities provided by Division biologists, estimates for the hydraulic escalator dredge are also available in Austin and Haven (1981), and MacPhail (1961).[14] These are converted to relative productivities by treating the hand gear productivities as numeraire, with other gear type productivities converted to a multiple of that numeraire. These data are presented in Table 3.

Estimation Results and Hypotheses Test.

The estimated parameters of equation (18) and additional summary statistics are presented in Table 4.

The results show that the mean values of output elasticities of effort (α) and stock (β) are both less than one. This implies that the production function of the North Carolina hard clam fishery exhibits

---

[14]The productivity of hydraulic escalator is estimated from 8 (Austin and Haven, 1981) to 60 (MacPhail, 1961) times that of conventional hand gear.

TABLE 3

DATA FOR ESTIMATING GROWTH AND TECHNICAL PRODUCTION FUNCTION FOR THE NORTH CAROLINA HARD CLAM FISHERY (1956-81)

Year	Meat, Q (lb.)	R	D	K	HYDR	E
1956	147,724	76	16	-	-	8932
57	243,135	137	17	-	-	12581
58	277,552	178	10	-	-	12760
59	339,385	230	10	-	-	15620
60	335,782	209	19	-	-	17133
61	369,964	238	21	-	-	19327
62	225,108	229	16	-	-	17317
63	320,279	250	26	-	-	21472
64	255,285	196	23	-	-	17611
65	312.904	203	22	-	-	17699
66	232,897	352	7	-	-	21439
67	200,223	348	2	-	-	19731
68	203,700	294	44	-	-	29238
69	252,659	219	-	-	14	22629
70	282,061	213	-	-	16	23811
71	253,506	177	-	8	16	24711
72	274,153	132	-	14	15	23640
73	379,573	149	-	20	17	28247
74	287,675	142	-	20	17	27862
75	285,089	117	-	10	19	24399
76	306,179	98	-	10	19	23351
77	739,066	101	-	135	19	68519
78	892,235	464	-	156	17	94532
79	1,449,700	1,027	-	181	14	132229
80	1,541,719	2,008	-	343	6	238456
81	1,458,196	1,604	-	351	22	231212

Notes:

1. Q = landings in pounds of meat,

   R = number of hand gear licenses including rakes and tongs

   D = number of dredge licenses

   K = number of kicking licenses

   HYDR = number of hydraulic escalator licenses

   E = constructed aggregate fishing effort index

2. The working days for each gear type per year are estimated as follows:

Hand gear and dredges: 110 days

Kicking: 40 days

Hydraulic escalator: 70 days

Assumption: 50 percent of those fisherman who held hand gear licenses will work on good working days: 90 percent of those who held other types of gear will work on the good working days.

3. Relative productivities:

Hand gear: 2,000-2,500 clams per day; used as a numeraire; productivity index =1

Dredge (before 1968): productivity index =3

Hydraulic Escalator: 125 bags per day, 250 clams per bag; productivity index = 125x250/2500≈12

Kicking: productivity index =10

4. Computation of effort index:

ER=Rx1x110x.5;

ED=Dx3x110x.9;

EK=Kx10x40x.9;

EH=HYDRx12x70x.9;

E=ER+ED+EK+EH.

Source:

1. Statistical Digest, Fishery Statistics of the United States., (U.S. Dept. of the Interior, Fish and Wildlife Service, 1955-67).

2. Fishery Statistics of the United States., (U.S. Dept. of Commerce, NOAA, ΣAA, NMFS 1968-76).

3. Current Fisheries Statistics: North Carolina Landings, Annual Summary, (U.S. Dept. of Commerce, 1961-76).

4. Unpublished Data, North Carolina Division of Marine Fisheries, Morehead City, NC 28557, 1977-1981.

TABLE 4

ESTIMATED PARAMETERS OF POPULATION DYNAMICS-FULL MODEL.

Parameters	Estimate	Asymptotic Standard Error
α	.66313151	.12736598
β	.65883589	.09221545
q	.00424053	.12647997
m	.48282769	.52983227
n	1.216776E-8	.00000056

SSE = .87548817 d.f. = 20

MSE = .04377441

MSY = m^2 /4n = 478,976

Asymptotic Correlation Matrix of the Parameters

	α	β	q	m	n
α	1.0	-.542644	.662051	.671228	.688919
β	- .542644	1.0	-.971788	-.880219	-.965629
q	.662051	-.971788	1.0	.917854	.999294
m	.671228	-.880219	.917854	1.0	.923437
n	-.688919	-.965629	.999294	.923437	1.0

decreasing returns to scale with respect to fishing effort and fish stock. Doubling fishing effort or fish stock will result in less than doubling of the harvest rate. Although these two parameters are estimated with reasonable precision, the estimates of the catchability coefficient (q) and population parameters (m and n) present considerable variations (relatively large asymptotic standard errors). In addition, the estimated mean value of maximum sustainable yield of 478,976 pounds of clam meats seems unrealistic, since average landings have been more than three times this value since 1979. High correlations among parameters (as shown in asymptotic correlation matrix) present another problem. Therefore, the estimated mean values of the full model are not reliable for computing maximum sustainable yield.

For the purpose of hypothesis tests, equation (18) is re-estimated by restricting α=1 and β=1 individually and jointly. The restricted model for α=1 is to test for the unitary output elasticity of effort or the noncongestion hypothesis; the restriction, β=1, tests for Smith's hypothesis of unitary output elasticity of stock; and finally α=1 and β=1 jointly is to test for the catch-per-unit-effort (CPUE) hypothesis. The results of these restricted models exhibited in Tables 5, 6 and 7.

The likelihood ratio test is used to determine whether these assumptions lead to a statistically significant increase in the sum of squares of error (SSE) of the model. The likelihood ratio, distributed as F, is calculated as

$$F = \frac{SSE(\tilde{\theta}) - SSE(\hat{\theta})]/r}{SSE(\hat{\theta})/(n-p)}$$

where

$SSE(\tilde{\theta})$ = restricted Sum Square of error

$SSE(\hat{\theta})$ = unrestricted Sum Square of error

r = number of restriction

p = number of unrestricted parameters to be estimated

n = number of observations used in estimation.

Table 8 summarizes the results of the hypotheses tested in Tables 5-7.

The estimate of the output elasticities of effort and stock in the North Carolina clam fishery are jointly not significantly different from unity. Thus, the statistical result fails to reject the CPUE hypothesis. The tests also show that the output elasticity of stock (β) is not significantly different from one, suggesting that saturation of fishing gear has not been a problem in the past 20 years. However, the parameter α shows a significant statistical difference from one at the 5 percent level. This suggests that there was a significant congestion problem of fishing vessels. In other words, the aggregate production function in the North Carolina hard clam fishery exhibited decreasing returns to scale in fishing effort. This is similar to Smith's (1980) findings in the lobster fishery.

Based on the landings data, this study estimates that the maximum sustainable yield for the North Carolina hard clam is around two million pounds of meats per annum. To test for this hypothesis, a

TABLE 5

ESTIMATED PARAMETERS OF POPULATION DYNAMICS-RESTRICTED MODEL

FOR $\alpha = 1$

Parameters	Estimate	Asymptotic Standard Error
β	1.0	.51124694
q	1.410292E-6	.00000447
m	.27946720	.23864424
n	2.717441E-8	.00000014

SSE = 1.17485251 d.f.=21

H_0: $\alpha = 1$; F = 6.84 significant at 5 percent level.

Asymptotic Correlation Matrix of the Parameters

	β	q	m	n
β	1.000000	-.975498	-.546606	.973609
q	-.975498	1.00000	.657403	-.904867
m	-.546606	.657403	1.00000	-.356791
n	.973609	-.904867	-.356791	1.00000

TABLE 6

ESTIMATED PARAMETERS OF POPULATION DYNAMICS-RESTRICTED MODEL FOR β=1

Parameters	Estimate	Asymptotic Standard Error
α	.68104332	.12240703
q	1.452105E-5	.00005260
m	.47212909	.20080274
n	1.915265E-8	.00000009

SSE=.87774418 d.f.=21

H_0: β =1; F=.05 insignificant at 5 percent level.

Asymptotic Correlation Matrix of the Parameters

	α	q	m	n
α	1.000000	.583350	.261508	.756754
q	.583350	1.00000	.271638	.967374
m	.261508	.271638	1.00000	.376506
n	.756754	.967374	.376506	1.00000

TABLE 7

ESTIMATED PARAMETERS OF POPULATION DYNAMICS-RESTRICTED MODEL FOR $\alpha=1$ and $\beta=1$

Parameters	Estimate	Asymptotic Standard Error
q	1.410292E-6	.00000096
m	.27946720	.19524376
n	2.717441E-8	.00000003

SSE=1.17485251 d.f.=22

H_0: $\alpha=\beta=1$; F=3.42 insignificant at 5 percent level.

Asymptotic Correlation Matrix of the Parameters

	q	m	n
q	1.000000	.674090	.893943
m	.674090	1.00000	.917731
n	.893943	.917731	1.00000

TABLE 8

SUMMARY OF HYPOTHESIS TESTS

Restricted Parameters	$SSE(\tilde{\theta})$	F value	F critical value at 5%
$\alpha=1$ & $\beta=1$	1.17485251	3.42	$F^*(2,20) = 3.49$
$\alpha=1$	1.17485251	6.84	$F^*(1,20) = 4.35$
$\beta=1$	.87774418	.05	$F^*(1,20) = 4.35$

model with restrictions of $\beta=1$ and MSY=2 million[15] imposed on equation (18) is rerun using the same estimating procedure as the full model. The results are shown in Table 9.

The corresponding likelihood ratio test with F=.014 indicates that the maximum sustainable yield is not significantly different from two million pounds of meats per annum. Though recent peak landings of 1.7 million pounds is close to the MSY value, the suspected biological over-fishing problem does not appear to be serious yet.

Estimation of Production Costs.

The total annual production costs in the North Carolina hard clam fishery include operating costs from three major types of gear--hand gear, the hydraulic escalator dredge and clam kicking (otter trawl).

[15]Since $MST=m^2/4n$, the restriction of MSY=2 million is equivalent to imposing $m=\sqrt{8n} \times 1000$.

TABLE 9

ESTIMATED PARAMETERS OF POPULATION DYNAMICS-RESTRICTED MODEL

FOR β=1 AND MSY=2 MILLION POUNDS OF MEAT

Parameters	Estimate	Asymptotic Standard Error
α	.68958094	.11568790
q	.00001966	.00003869
n	2.784384E-8	.00000007

SSE=.87832521 d.f.=22

H_0: MSY=2 million; F=.014 insignificant at 5 percent level.

Asymptotic Correlation Matrix of the Parameters

	α	q	n
α	1.000000	.344430	.715276
q	.344430	1.00000	.901679
n	.715276	.901679	1.00000

For the purpose of estimating marginal cost, only variable costs associated with each gear type will be included.

Hand Gear.

Hand gear such as rakes and tongs are effective in shallow water or on beds exposed at low tide. Most fishermen operate hand gear by wading on the shallow beds during the low tidal cycle, which lasts approximately four hours each working day. Some of them work from the deck of a small vessel. So for the fishermen using hand gear, the investment in a boat, a motor and gear is relatively small,[16] (Tiller, Glude and Stringer, 1952, and communication with Mr. Munden, DMF).

Variable costs -- the cost associated with actual harvesting activities - include two principal components: (1) fuel cost and (2) opportunity cost of the fisherman. Conrad (1981) estimates that fuel cost of operating a small vessel over four hours of harvesting activities is $5 in 1981. Since the proportion of fishermen using vessels in hand gear harvesting in North Carolina is relatively small and unknown, the fuel cost of operating small vessels for hand gear is ignored in this study.

The opportunity cost of a fisherman reflects what the fisherman could have earned in his next best employment activity. Alternative employment opportunities will vary from individual to individual and from season to season because most fishermen holding hand gear licenses are part-time fishermen who usually turn to other fisheries whenever

[16]The fixed cost payments for the similar situation incurred in Great South Bay are estimated ranging between $500 and $1,000 per year (Conrad, 1981).

relatively profitable. It was assumed that the opportunity cost of th fisherman's time was $5 per hour in 1981. Therefore, the total annual opportunity costs (working for four hours per day, and 110 days per year) per hand gear license is estimated to be $2,200, which is equivalent to $808 after conversion to 1967 dollars (deflating $2,200 by 272.3, which is the CPI for all items in 1981).

Clam Kicking.

Kicking is generally restricted to water 10 feet deep or less, (Guthrie and Lewis, 1982). Usually, one captain and one or two crew members fish together. A frequent practice in the N.C. fishery is the division of income from a day's catch where one-third of the gross revenue covers operating expenses (including fuel costs), one-third goes to the owner and one-third to the crew member(s). This practice often applies to clam kicking. No published cost information relates to clam kicking in North Carolina. But many fishermen who kick clams also shrimp, and the cost structures of the two fisheries are similar. Maintenance and fuel costs are higher for kicking, however. Waters (1983) has made a thorough survey of the published annual budgets for shrimp trawlers (for details, see Waters 1983, p.58). Among those surveyed budgets, Liao's (1979) cost information is adopted in the current study, since they were based on the most recent information for the southern Atlantic states, including North Carolina. Hence, annual operating costs per license issued for clam kicking are derived from Table 21 of Liao's (1979) budgets for mobility class I trawlers, with adjustments in working days and costs for fuel and maintenance. In addition, it is assumed that cost of fuel and maintenance for clam kicking is 20 percent higher than for operating shrimp trawlers. Table 10 summarizes the annual variable costs per license of operating a clam kicking vessel. Total annual variable costs per license of \$3,529 in 1976 is equivalent to \$2,080 in 1967 price levels (CPI for all items in 1976 = 170.5).

Hydraulic Escalator Dredge.

Hydraulic escalator dredges generally fish at depths of 4 to 15 feet, although some can work deeper. Crew size is generally three or four. But in most cases, the hydraulic escalator dredge is operated by family members. In 1981-1982, the investment in the first-class hydraulic escalator dredge 30 to 40 feet long, with 10 to 20 years expected life, was estimated as \$40,000-80,000 for the vessel and \$10,000-15,000 for the harvest mechanics. Annual maintenance cost is approximately \$5,000 (personal communication with Munden, 1982). Costs for fuel are estimated as \$3,000 per day. Therefore total annual variable costs of operating the dredge are approximately \$3,000 in 1967 price levels.[17]

Estimation of Cost Coefficient, c.

As described in the previous chapter, cost is assumed to be proportional to fishing effort so that C(t)=cE(t). The index of aggregate fishing effort, E(t), is shown in Table 3. Estimated annual total operating costs, C(t), are computed according to the following:

$$C(t)=\sum_{i=1} \text{(variable costs of operating gear type i)} \cdot \text{(number of licenses of gear type i)} \cdot \text{(proportion of individuals holding a license of gear type i that will fish on a good working day)}.$$

---

[17] \$8,000/272.3 x 100 = 2,938 $\simeq$ 3,000 (CPI(1981)=272.3)

TABLE 10

ANNUAL VARIABLE COSTS PER CLAM KICKING
LICENSE OF OPERATING CLAM KICKING IN 1976

Variable Cost Components	Liao's Budget[a/]	Adjusted Budgets
Fuel	3205	1326[b/]
Repair & Maintenance	3612	1495[b/]
Other	2052	728[c/]
Total annual variable costs per license	$ 8869	$ 3529

a/. Liao's 1976 cost information: from Table 21 of an economic analysis of the mobility of shrimp vessels in the South Atlantic states (Liao, 1979).

b/. Adjusted budgets = Liao's budgets x 1.2 x 40/116, since costs are assumed 20 percent higher for fuel and maintenance, and clam kicking averages 40 days while shrimp trawlers are operated for 116 days.

c/. Adjusted budgets = Liao's budgets x 40/116.

"Other" costs includes ice which is not used in the clam kicking operation. The estimated adjusted ice costs is $244 per year in 1976 dollars.

IV. AN ECONOMIC ANALYSIS OF THE NORTH CAROLINA EX-VESSEL HARD CLAM MARKET

Chapter III estimated the model components that provide a basis for deriving the optimally controlled supply curve. This chapter presents the empirical study of the ex-vessel or landings market for hard clams in North Carolina. North Carolina hard clam demand and supply functions are estimated using a simultaneous equation model. The estimated supply curve is then contrasted with the optimally controlled supply curve to determine whether biological and/or economic overfishing has occurred in the past. Variable costs of operating various gear types are discussed in the above sections. Number of licenses for different gear types and the proportion of the number of different gear types that will fish on a working day are shown in Table 3. Estimated operating costs and fishing effort for the periods 1969 to 1981 are summarized in Table 11. The cost coefficient, c, is determined by linear regression,

$$C(t)=cE(t)+e(t).$$

Table 12 presents the regression result. The estimated cost coefficient is $5.94 in 1967 price levels.

The Empirical Model - A Simultaneous Approach.

Most empirical studies on seafood products focus on the price flexibilities derived from an estimated inverse demand equation. Usually the supply curve is assumed, either implicitly or explicitly,

TABLE 11

ESTIMATED OPERATING COSTS AND FISHING EFFORT (1969-81)

Year	CR	CK	CH	C	E
			(in 1967 price level)		
1969	88476	--	37800	126276	22629
1970	6052	--	43200	129252	23811
1971	71508	14976	43200	129684	24711
1972	53328	26208	40500	120036	23640
1973	60196	37440	45900	143536	28247
1974	57368	37440	45900	140708	27862
1975	47268	18720	51300	117288	24399
1976	39592	18720	51300	109612	23351
1977	40804	252720	51300	344824	68519
1978	187456	292032	45900	525388	94532
1979	414908	338832	37800	791540	132229
1980	811232	642096	16200	1469528	238456
1981	648016	657072	59400	1364488	231212

Notes: 1. CR = total annual variable costs of operating hand rakes = 808 x R x 0.5

CK = total annual variable costs of operating clam kicking vessels = 2080 x K x 0.9

CH = total annual variable costs of operating hydraulic escalator dredges = 3000 x HYDR x 0.9

C = CR + CK + CH.

2. R, K and HYDR are the number of licenses issued for hand rakes, clam kicking and hydraulic escalator dredges; E is the index of aggregate fishing effort. Those numbers are summarized from Table 3.

TABLE 12

LINEAR REGRESSION RESULT FOR $C(t)=c\ E(t)+e(t)$

Parameter	Estimate	Standard Error	t value
c	5.937425	.082108	72.312*

* significant at one percent level: without ice included in variable costs the estimate of c would be 5.935819 which is reduction of approximately 0.03 percent. Therefore, no correction was made for the difference in ice costs.

The two-equation system is specified as follows:

$$\text{Demand: } P(t)=\beta_0 OTHER+\beta_2 YUSA+\beta_3 SURF+\beta_4 SOFT+e(t) \quad (19)$$

$$\text{Supply: } Q(t)=\tau_0+\tau_1 P(t)+\tau_2 RAKE+v(t) \quad (20)$$

where

- $Q(t)$ = the annual North Carolina landings of hard clam in thousand pounds of meat
- $P(t)$ = the ex-vessel North Carolina hard clam price in cents per pound of meat, deflated by consumer price index (all items, unadjusted series)
- OTHER = total clam landings in thousand pounds of meat from other states in the U.S.A.
- YUSA = per capita U.S. disposable personal income, deflated by consumer price index (all items, unadjusted series)
- SURF = U.S. total landings of surf clams in thousand pounds of meat
- SOFT = U.S. total landings of soft clams in thousand pounds of meat
- RAKE = number of rake gear units registered in North Carolina

to be perfectly inelastic when monthly data are used because of perishability. If the demand curve is relatively stable, then the observed market price and quantity relationship is assumed to trace out the demand equation. But when this is not the case, a single equation approach may result in identifying a supply equation instead of a demand equation, with biased estimates resulting. Strand (1976) performed a limited-price analysis of the hard clam fishery of the eastern shore of Virginia. He concluded that both landings and real ex-vessel prices were declining. Conrad (1980) analyzed wholesale prices of hard clams over a 40-week period at the Fulton Market in New York. He concluded hard clam wholesale prices at the market were inflexible for clams with respect to the quantity sold,[18] without being able to identify the major determinant of the wholesale price (Kvaternik, DuPaul and Murray 1983). Capps, Shabman and Brown (1984) used four simultaneous equations to model the price formation process at the wholesale and ex-vessel levels for the U.S. hard clam fishery. There has been no economic analysis for the North Carolina hard clam fishery. The current study employs a simultaneous system to eliminate potential simultaneous equation bias.

The Inverse Demand Equation.

From 1960 to 1982, North Carolina hard clam landings constituted a small proportion of the U.S. total landings (less than 3 percent before

---

[18]The Fulton Fish Market in New York City physically handles about 10 percent of the entire U.S. hard clam harvest and serves as the industry price leader (Capps, Shabman and Brown, 1984). It is surprising that the wholesale price at Fulton Market was found to be perfectly elastic.

1976, and only slightly more than 10 percent in 1979 and 1980). Therefore the North Carolina hard clam fishery is assumed to be a price taker. The inverse demand equation using price as a dependent variable is therefore adopted in this study. Landings from North Carolina, Q(t), were initially included in the price equation in an attempt to test statistically for the hypothesis of price-taker. Unfortunately, the estimated parameter has shown a significant positive number, which violates the law of demand and contradicts the practice confirmed by the clam dealers that the North Carolina clam fishery is a price-taker. The variable Q(t) is therefore dropped from the price equation. Hard clam landings from other states, and landings of surf and soft clams are included because they are close substitutes for North Carolina hard clams. Accordingly, these variables are hypothesized to be negatively related to the ex-vessel price of North Carolina hard clams.[19] The logic is: a larger supply of a substitute results in a lower price for that substitute, which in turn results in a decline in demand for the commodity in question. The lower demand implies a reduction in price. Therefore a larger supply of the substitute reduces the price of the commodity under consideration.

In addition, U.S. per capita disposable personal income is used as another demand shifter because it is reported that more than 90 percent of the North Carolina hard clams are shipped to northern markets and other states (for example, Florida and California) for processing or resale as shell stock (Street 1976, Maiolo and Tschetter 1983). YUSA

[19]This is in contrast to an usually positive relationship between the quantity demanded of a commodity and the price of its substitutes in an ordinary specification of demand equation.

is expected to be positively related to the ex-vessel price, since price moves directly with the shift in demand. A higher per capita disposable personal income implies a larger demand, and this suggests a higher price for any given quantity.

The Supply Equation.

As shown in Table 3, fishing effort and landings were relatively stable before 1976. Since 1977, the extremely high demand from northern states has resulted in rapidly increasing prices and induced greater fishing effort. Evidence of this shift in fishing effort can be seen by examining Table 3. The number of units of rake licenses increased four-fold in 1978 from the previous year and more than 10 times since 1978. Such growth might be explained in part by very low entry and exit costs. Harvesting clams using hand gear often acts as a buffer job for temporarily unemployed labor. Therefore, the number of units of rake licenses is used as a supply shifter, which is hypothesized to be positively related to landings.

The Procedure and Data.

Since the total number of exogeneous variables in the system (k=6) is greater than the total number of parameters in either demand (N1=5) or supply equation (N2=3) to be estimated, the system of equations defined by (19) and (20) is said to be over-identified. Therefore, the two-stage least square (2SLS) procedure is used to estimate the coefficients. Table 13 exhibits the data used in 2SLS regression.

The Empirical Results.

A summary of the estimation of the coefficients of the above market model for the years 1960 to 1982 is shown in Table 14. The overall F value of 22.05 and 173.39 for demand and supply respectively indicates that the proposed explanatory variables in the demand and supply equations jointly have significant effects on the price and quantity. The R^2 values of .83 and .95 for demand and supply indicate a good fit for the data. Signs on all parameter estimates conform to *a priori* expectations, and all parameter estimates except the intercept term in the demand equation show a significant statistical difference from zero at the 10 percent level. The Durbin-Watson test has shown that there is no serial auto-correlation in the supply equation at the 1 percent level. But the Durbin-Watson test is inconclusive in the demand equation.

As shown in Table 13, the number of units of rake licenses were fairly stable around 250 units before 1970 and have fluctuated with considerable range since then. This fact may suggest two different supply curves for these two periods. Another 2SLS regression is performed using the demand function specified in equation (19) and the following modified supply equation:

$$Q(t)=r_0+r_1 \cdot p(t)+r_2 \cdot RAKE+r_3 \cdot D+r_4 \cdot D \cdot p(t)+r_5 \cdot D \cdot RAKE+V(t)$$

where D is a dummy variable with D=0 standing for the period 1971 to 1982 and D=1 for 1960 to 1970. The estimation results of the demand equation remain the same. The estimated coefficients of the modified supply equation are presented below with the standard error in parenthesis.

TABLE 13

DATA USED IN 2SLS REGRESSION

Year	QTOT 1/	VNC 2/	QNC 2/	DPIUSA 3/	SOFT 1/	SURF 1/	RAKE 4/	CPI 5/
1960	14877	134	336	1938	8579	25071	209	88.7
1961	14604	148	370	1981	7363	27502	238	89.6
1962	13295	90	225	2065	9396	20854	229	90.6
1963	14529	125	320	2135	9754	38586	250	91.7
1964	14925	98	255	2286	11030	38144	196	92.9
1965	15044	137	313	2438	11308	44088	203	94.5
1966	15324	94	233	2602	11919	45113	352	97.2
1967	16182	106	200	2747	9823	45054	348	100.0
1968	15426	117	204	2947	10368	40552	294	104.2
1969	16154	141	253	3144	13481	49575	219	109.8
1970	16015	157	282	3382	12908	67318	213	116.3
1971	16666	148	254	3608	12652	52535	177	121.3
1972	16153	163	274	3846	9078	63471	132	125.3
1973	14505	294	380	4302	8627	82370	149	133.1
1974	15008	322	288	4655	8594	96110	142	147.7
1975	14827	226	285	5063	8759	86919	117	161.2
1976	15600	258	306	5468	10540	49133	98	170.5
1977	15433	1069	739	5957	10683	51036	101	181.5
1978	13295	2449	892	6614	10091	39237	464	195.3
1979	12058	4474	1450	7320	8581	34912	1027	217.7
1980	13370	5554	1542	8025	8948	37737	2008	247.0
1981	18118	5387	1458	8897	8072	46100	1604	272.3
1982	12855	6606	1702	9375	8021	49720	2000	288.6

Notes: 1. Original Data

QTOT– total U.S. hard clam landings, in thousand pounds of meat;

VNC– ex-vessel values of N.C. hard clam landings, in thousand dollars;

QNC– North Carolina hard clam landings, in thousand pounds of meat;

DPIUSA– per capita U.S. disposable personal income, in current dollars;

SOFT– total U.S. soft clam landings, in thousand pounds of meat;

SURF– total U.S. surf clam landings, in thousand pounds of meat;

RAKE– number of rake gear type registered in North Carolina;

CPI – consumer price index, all items, unadjusted series.

2. Data Transformation:

$P(t)=(VNC/QNC)/CPI \times 100 \times 100;$

$OTHER= QTOT - QNC;$

$Q(t)=QNC;$

$YUSA= DPIUSA/CPI \times 100.$

Source: 1. a) Shellfish Market Review and Outlook - Current Economic analysis, Total landings of clams by species, annual summary, (U.S. Dept.of Commerce, 1960-81);

b) Fisheries of the United States, 1982, April 1983, (U.S. Dept. of Commerce, NOAA/NMFS).

2. a) Current Fisheries Statistics: North Carolina Landings, Annual Summary, (U.S. Dept. of commerce 1960-1979);

b) North Carolina Landings, (N.C. Dept. of Natural Resources and Community Development 1980-1982).

3. Survey of Current Business, Table 4, Aug. 1982; Table 1, Aug. 1983, (U.S. Dept. of Commerce/Bureau of Economic Analysis).

4. a) Statistical Digest, Fishery Statistics of the United States, (U.S. Dept. of the Interior, Fish and Wildlife Service, 1960-1967);

b) Fishery Statistics of the United States., (U.S. Dept. of Commerce, NOAA/IAA/NMFS 1968-1976);

c) Unpublished Data, North Carolina Division of Marine Fisheries, Morehead City, NC 28557.

5. a) Historical Statistics of the United States, Colonial Times to 1970, Bicenlennical Edition, Part 1, (U.S. Dept. of Commerce, Bureau of the Census, p.210);

b) Statistical Abstract of the United States, 102 ed., National Data Book and Guide to Sources, (U.S. Dept. of Commerce, Bureau of the Census, p.468, 1971-1982).

TABLE 14

ESTIMATES OF THE STRUCTURAL COEFFICIENTS FOR SIMULTANEOUS EQUATIONS MODEL OF THE NORTH CAROLINA HARD CLAM MARKET

Parameter	Estimate	t value	Other Statistics
Demand:			
β_0	9.05	.16	R^2 = .83
β_1	-0.0055	-1.85**	F = 22.05*
β_2	0.0817	6.72*	DW= 1.52
β_3	-0.0052	-2.03**	
β_4	-0.0009	-3.58**	
Supply:			
γ_0	-190.37	-2.67**	R^2 = .95
γ_1	8.3415	5.92*	F= 173.39*
γ_2	0.3195	3.65*	DW = 2.29

* significant at 1%.

** significant at 10%.

$\tau_0 = -240.8786 \quad (132.9331)$

$\tau_1 = 9.2420 \quad (2.0162)$

$\tau_2 = .2792 \quad (.1038)$

$\tau_3 = 1008.201 \quad (433.3672)$

$\tau_4 = -17.9907 \quad (9.2678)$

$\tau_5 = -.6312 \quad (.7288)$

The coefficients of τ_1, τ_2, and τ_3 are significant at the 5 percent level and τ_4 is significant at the 10 percent level. The mean square error (MSE) test is performed to see whether the specification shown above is statistically different from the one specified in equation (20). (For detailed discussions of MSE test, see Wallace 1977). The F value of .82 shows that it is not significantly different.

Another problem associated with the variable RAKE is that RAKE may be endogeneous. Since RAKE is a type of fishing effort (an input of production), it may depend on the "price" of the hard clam. If this is the case, the variable p(t) and RAKE are correlated and there would be a multicollinearity problem. But the input decision is usually made before the market price is known. Therefore, the variable RAKE may depend on the "expected price" rather than the concurrent "price." The estimated results of the coefficients presented above and in Table 14 are significant. These results indicate that there is no multicollinearity problem. Hence the potential endogeneity problem is not of concern in this study.

Price Flexibilities, Elasticities and Economic Interpretation.

Price Flexibilities .

The price flexibility coefficient gives the percentage change in price associated with a 1 percent change in quantity, other factors constant. Other flexibility coefficients such as the flexibility with respect to income and cross flexibility are analogous to the concept of income elasticity and cross elasticity. These flexibility coefficients are important parameters that are frequently computed from inverse demand equation (Tomek and Robinson 1972).

The price flexibility with respect to income is the percentage change in price in response to a 1 percent change in income, other factors remaining constant. In notation, it is calculated as follows:

$$F_{P,YUSA} = \frac{\%P}{\%YUSA} = \frac{dP}{dYUSA} \cdot \frac{YUSA}{P} \quad .$$

The cross flexibility with respect to Qj is the percentage change in the price of the commodity under consideration in response to a 1 percent change in the quantity of commodity j, other factors remaining constant. The algebraic relationship is as follows:

$$F_{P,j} = \frac{\%P}{\%Qj} = \frac{dP}{dQj} \cdot (Qj/P) \quad .$$

Using the empirical results shown in Table 14, the flexibility coefficients (evaluated at mean values) are calculated as follows:

$$F_{P,YUSA} = \frac{dP}{dYUSA} \cdot \frac{YUSA}{P} = (.0817)\frac{2897}{70.36} = 3.36$$

$$F_{P,OTHER} = \frac{dP}{dOTHER} \cdot \frac{OTHER}{P} = (-.0055)\frac{14422}{70.36} = -1.13$$

$$F_{P,SURF} = \frac{dP}{dSURF} \cdot \frac{SURF}{P} = (-.0052)\frac{9938}{70.36} = -.73$$

$$F_{P,SOFT} = \frac{dP}{dSOFT} \cdot \frac{SOFT}{P} = (-.0009)\frac{49180}{70.36} = -.63$$

The flexibilities show the North Carolina ex-vessel price per pound of clam meats to be flexible with respect to U.S. real per capita disposable personal income and the hard clam landings of other states, but inflexible with respect to total soft and surf clam landings.[20] At the sample mean value for price, income and other states' landings, the price per pound of meat increases approximately 3.36 percent in response to a 1 percent increase in U.S. real per capita personal income; and 1.13 percent in response to a 1 percent decrease in other states' hard clam landings. The ex-vessel hard clam price received by fishermen in North Carolina is less affected by charges in soft and surf clam landings. The price per pound drops .73 percent with a 1

---

[20]If the absolute value of the flexibility coefficient is greater than one (less than one), demand is said to be price flexible (price inflexible).

percent increase in soft clam landings and .63 percent with a 1 percent increase in surf clam landings.

The relative magnitudes of flexibilities of hard clam landings from other states and of surf and soft clam landings are reasonable, because hard clam landings from other states are close substitutes for the North Carolina hard clam, while surf and soft clams are apparently substitutes for the larger "chowder" hard clam only.

Supply Elasticities.

Supply elasticities evaluated at mean values with respect to price and the supply shifter (RAKE) are shown below.

$$E_{Q,P} = \frac{dQ}{dP} \cdot \frac{P}{Q} = 8.3415 \cdot \frac{70.36}{546.13} = 1.07$$

$$E_{Q,RAKE} = \frac{dQ}{dRAKE} \cdot \frac{RAKE}{Q} = .3195 \cdot \frac{468.26}{546.13} = .27$$

The price elasticity of supply suggests that hard clam landings are relatively responsive to ex-vessel price changes. Any management policy, for example, a landing tax, that reduces the ex-vessel price received by the fisherman will effectively cut back the production by a percentage slightly greater than the increased tax rate. The elasticity of supply shifter of .27 implies that there is little effect of increased fishing effort using rakes on the hard clam landings. This number is misleading, because it is evaluated at its mean value over the past 20 years. Since 1979, the fishing effort using rakes has been more than two-fold that of mean value, while its landings in pounds of meat has been more than 60 percent of the total North Carolina landings. This recent boost is offset by previous years of minimal production in this analysis.

The Effect of Change in Economic Factors on the Hard Clam Landings in North Carolina.

Assuming that the system relations will remain approximately the same in the future, the effect of changes in economic factor j on hard clam landings in North Carolina can be depicted with the following equation:

$$N_{Q,j} = E_{Q,P} \cdot F_{P,j}$$

The calculated value of N for U.S. real per capita disposable personal income is 3.60, suggesting that the induced North Carolina hard clam landings will increase 3.60 percent in response to a 1 percent increase in U.S. real per capita disposable personal income. If U.S. real per capita disposable personal income grows at an annual rate of three percent, other things being equal, landings will increase at a 10.8 percent annual rate. Therefore, by the end of 1984, landings are expected to reach 2.09 million pounds (1.7 million (in 1982) x $1.108^2 = 2.09$ million (in 1984)), which is beyond the estimated maximum sustainable yield (2 million). The biological overfishing problem might have occurred earlier if other demand shifters had been compounded. Similarly, a 1 percent decrease in other states' hard clam landings is expected to induce 1.21 percent increase in North Carolina landings. Furthermore, the North Carolina landings are expected to increase by less than 1 percent associated with a 1 percent decrease in either surf clam or soft clam landings. In other words, the surf clam and soft clam fishery have less effect on North Carolina's hard clam fishery than other state's hard clam landings.

V. THE OPTIMALLY CONTROLLED SUPPLY CURVE VERSUS EMPIRICAL SUPPLY CURVE AND HISTORICAL DATA

Equations (9) and (10) together define the optimally controlled supply curve in general form. Given the specific functional forms discussed in Chapter II, the components of equation (9) are shown as follows:

$$C_Q(X,Q)=[c/(qX^{\beta})^{1/\alpha}](1/\alpha)Q^{(1/\alpha)-1}$$

$$C_X(X,Q)=c[Q/(qX^{(\beta+\alpha)})]^{1/\alpha}(-\beta/\alpha),$$

$$F'(X)=m-2nX.$$

Solving equation (10) in terms of Q yields

$$X=(m\pm\sqrt{m^2-4nQ})/2n.$$

The numerical solutions of the optimally sustainable yields, Q, corresponding to the prices can be obtained by using these specific functional forms and the results of estimated parameters of the population dynamics as shown in Table 9. Table 15 presents the price-quantity relationships for the steady-state supply curve using the discount rate, $\delta=0$, $\delta=.10$ and $\delta=.20$.

Figure 5 illustrates the steady-state supply curves based on Table 15. Since the stock effects are relatively large compared to the discount rates (for all three cases) over the relevant range of prices

TABLE 15

THE PRICES AND QUANTITIES FOR THE STEADY-STATE SUPPLY CURVE

Parameters: α=.7; β=1.0; c=5.94; n=.00000003; q=.00002

m= $\sqrt{8n}$ x1000=.4[illegible]9898; MSY=2 million pounds

Q	δ=0.0 Price (dollars)	δ=.1 Price (dollars)	δ=.2 Price (dollars)
		(1967 dollars)	
200,000	.4333	.4313	.4299
300,000	.5337	.5298	.5270
400,000	.6261	.6197	.6152
500,000	.7162	.7064	.6997
600,000	.8071	.7930	.7835
700,000	.9011	.8816	.8686
800,000	1.0007	.9742	.9569
900,000	1.1082	1.0727	1.0498
1,000,000	1.2265	1.1793	1.1494
1,100,000	1.3592	1.2967	1.2579
1,200,000	1.5114	1.4283	1.3779
1,300,000	1.6904	1.5791	1.5133

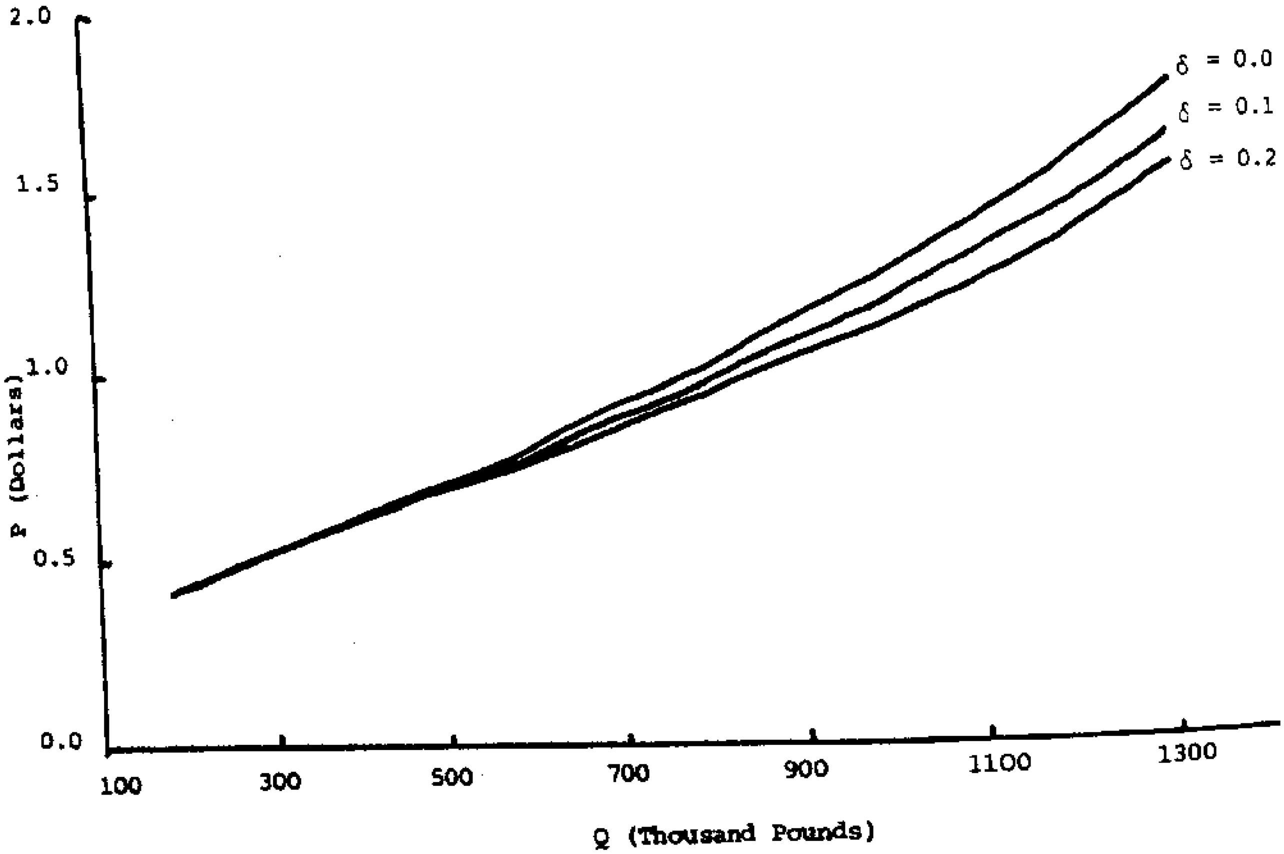

Figure 5: The Prices and Quantities for the Steady-state Curve with δ=0, 0.1 and 0.2.

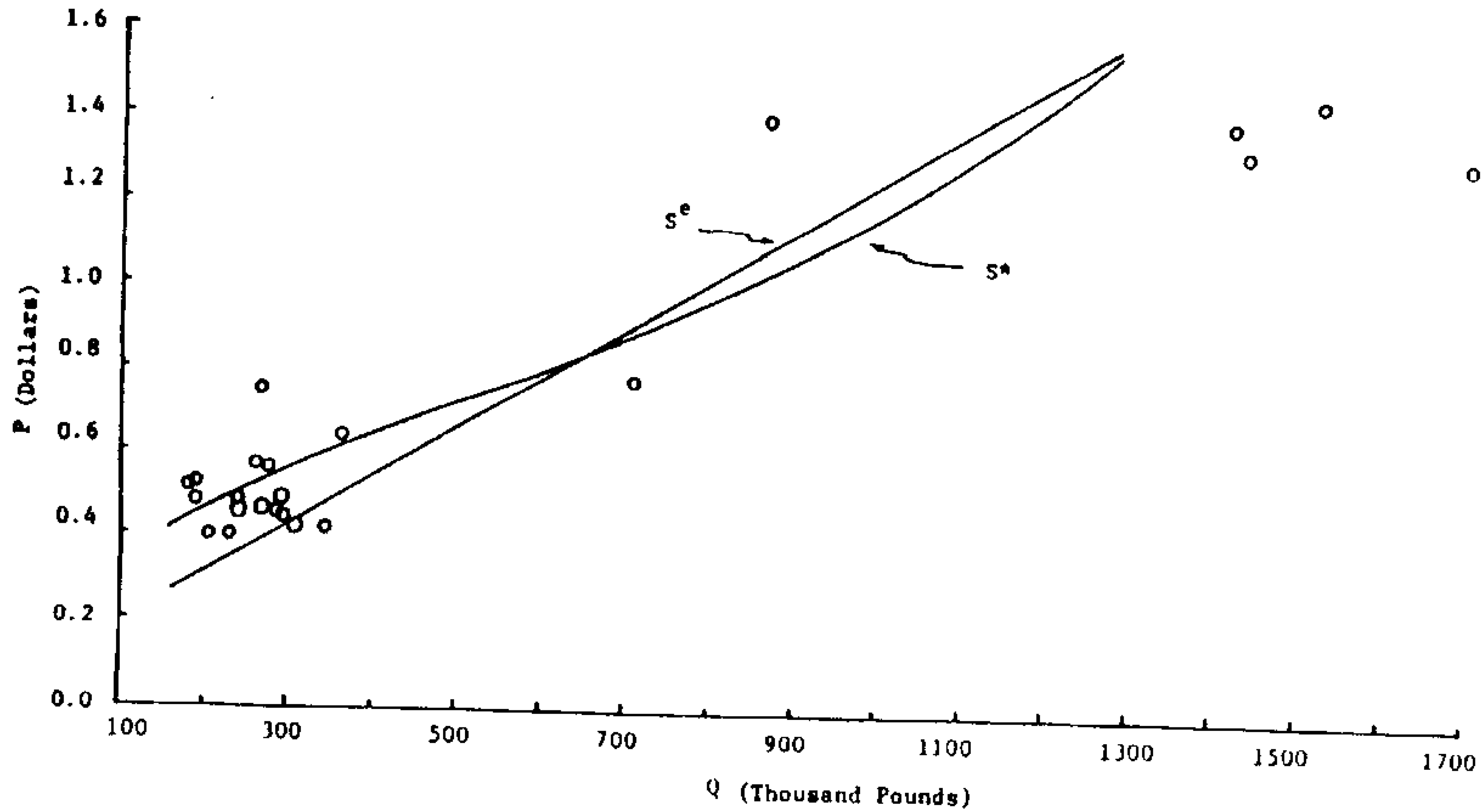

Figure 6: The Steady-state Supply Curve (S*), the Empirical Curve (S^e) and the Historical Records (indicated by scatter points).

under consideration, the effective discount rates discussed earlier are negative. This implies that the economically optimal steady-state stocks are larger than the stock with maximum biological sustainable yield (point c in Figure 1). Consequently, the optimal sustainable harvest rate is larger the higher the discount rate at any given price level. Figure 5 shows the increase in the optimal harvest rate, Q, brought about by the sensitivity of the discount rates to the level of sustainable yield. Intuitively, this follows as future benefits are discounted more heavily relative to current benefits. Hence the optimal policy requires a higher sustainable harvest rate and leaves less stock for future generations.

Assuming that the opportunity discount rate is 10 percent, the corresponding steady-state supply curve indicates the optimally sustainable harvest rate at each price level. Economic overfishing is said to occur if the actual harvest rate is greater than the optimally sustainable harvest rate. Although the biological overfishing problem does not appear serious yet, economic overfishing has occurred in the past and in recent years. Table 16 summarizes the historical record in contrast with the steady-state price-quantity figures.

As shown in Table 16, the North Carolina hard clam fishery has not operated with economic efficiency in 15 out of 23 years. The landings in 1982 (1.7 million pounds) exceeded the suggested optimal harvest rate (1.2 million pounds) by more than 40 percent. Figure 6 illustrates the steady-state supply curve, the empirical supply curve and the historical record. The empirical supply curve is derived from

TABLE 16

THE STEADY-STATE PRICE-QUANTITY (P*, Q*) RELATIONSHIP VERSUS THE HISTORICAL RECORDS (P+, Q+)

P*	Q*	Year	P+	Q+
		(1967 dollars)		
.4097	180,000	1964**	.4137	255,000
.4313	200,000	1966**	.4151	233,000
.4821	250,000	1963**	.4260	320,000
.5298	300,000	1962	.4415	225,000
.5754	350,000	1961**	.4464	370,000
.6197	400,000	1960**	.4496	336,000
.6632	450,000	1965**	.4632	313,000
.7064	500,000	1972**	.4748	274,000
.7496	550,000	1970**	.4787	282,000
.7930	600,000	1971**	.4804	254,000
.8369	650,000	1975	.4912	285,000
.8816	700,000	1976**	.4945	306,000
.9273	750,000	1969	.5076	253,000
.9742	800,000	1967	.5300	200,000
1.0226	850,000	1968	.5504	204,000
1.0727	900,000	1973	.5813	380,000
1.1249	950,000	1974	.7570	288,000
1.1793	1,000,000	1977**	.7970	739,000
1.2365	1,050,000	1982**	1.3449	1,702,000
1.2967	1,100,000	1981**	1.3569	1,458,000
1.3605	1,150,000	1978	1.4058	892,000
1.4283	1,200,000	1979**	1.4173	1,450,000
1.5010	1,250,000	1980**	1.4582	1,542,000

** economic overfishing

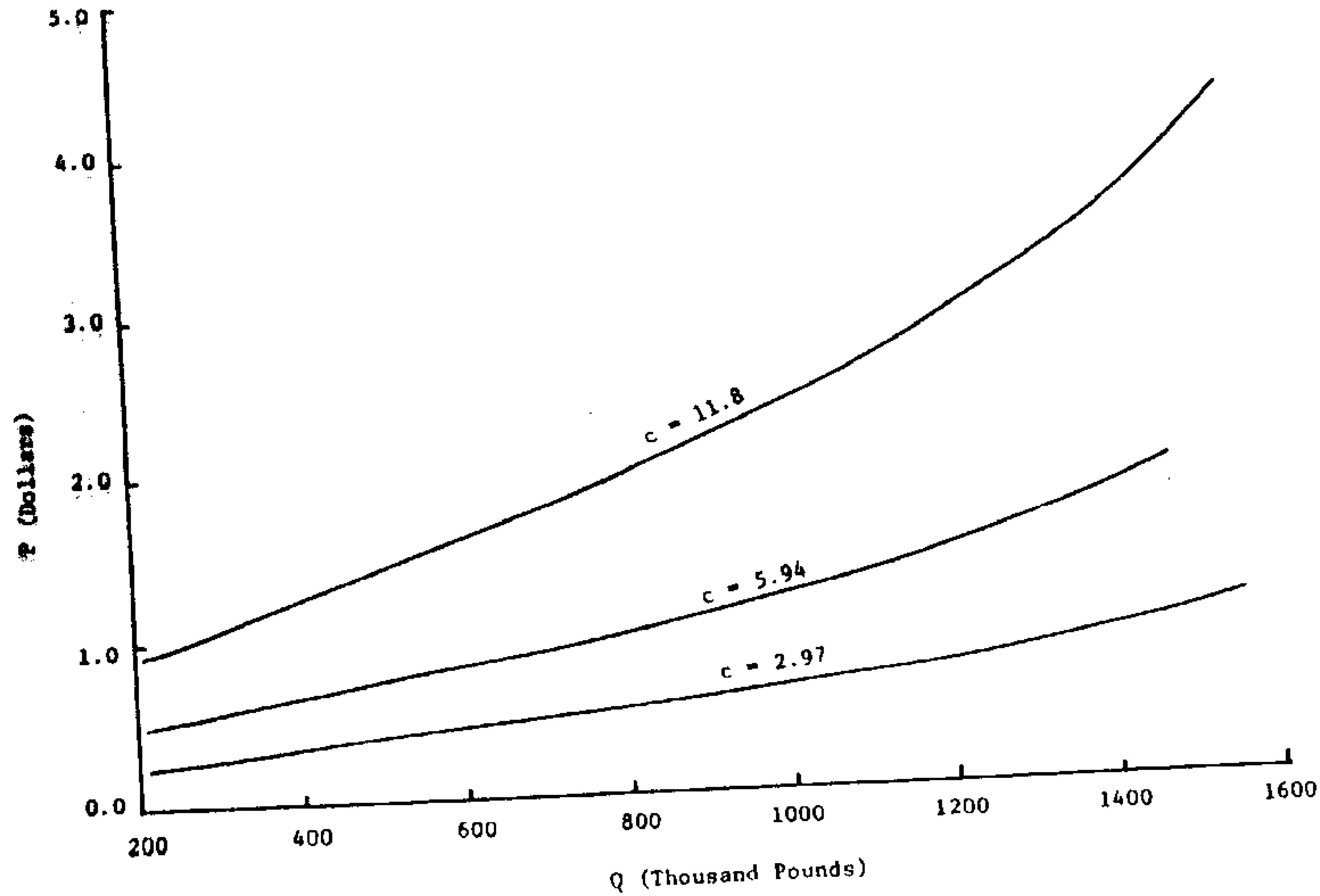

Figure 7: The Steady-state Prices (P*) and Quantities (Q*) Relationship for c=2.97, 5.94 and 11.8 .

Table 14 [evaluated at the mean value of number of rakes, 468.26]. If the number of licenses issued for hand gear had been kept around its mean value of 468, the predicted harvest rates in recent years would not have exceeded the optimal harvest rate. And economic efficiency would have been improved (economic overfishing reduced).

Furthermore, since cost plays an important role in determining the optimal harvest rate, a sensitivity analysis by contrasting the cost coefficient (c=$5.94) with halved (2.97) and doubled (11.88) cost is performed for reference (see Table 17 and Figure 7). Given the steady-state harvest rate, the corresponding required price level is positively related to the cost coefficient. In particular, since the cost is assumed to be proportional to fishing effort and the production function is assumed to take the form of a Cobb-Douglas function, the corresponding required price level is doubled when the cost coefficient is doubled. This proportional relationship can be obtained analytically by examining the components of equation (9) discussed at the beginning of this section.

VI. CONCLUSION AND SUGGESTION FOR FURTHER RESEARCH

Conclusion

The theoretical model developed in the early section of this report is used to derive a long-run (steady-state), optimally controlled supply curve for the North Carolina hard clam fishery. Chapter III presents the results of the estimated parameters including population dynamics and a harvesting cost function. The results have

TABLE 17

THE STEADY-STATE PRICE (P*) AND QUANTITIES (Q*) RELATIONSHIP FOR c=2.97, 5.94 and 11.88

Q*	c=2.97	c=5.94	c=11.88
	P*	P*	P*
	(1967 dollars)		
200,000	.2157	.4313	.8626
250,000	.2411	.4821	.9642
300,000	.2649	.5298	1.0595
350,000	.2877	.5754	1.1507
400,000	.3098	.6196	1.2393
450,000	.3316	.6632	1.3264
500,000	.3532	.7064	1.4128
550,000	.3748	.7496	1.4991
600,000	.3965	.7930	1.5859
650,000	.4185	.8369	1.6738
700,000	.4408	.8816	1.7632
750,000	.4637	.9273	1.8546
800,000	.4871	.9742	1.9484
850,000	.5113	1.0226	2.0452
900,000	.5364	1.0727	2.1455
950,000	.5624	1.1248	2.2497
1,000,000	.5897	1.1793	2.3587
1,050,000	.6182	1.2365	2.4729
1,100,000	.6484	1.2967	2.5934
1,150,000	.6802	1.3605	2.7209
1,200,000	.7142	1.4283	2.8567
1,250,000	.7505	1.5010	3.0019
1,300,000	.7896	1.5791	3.1582
1,350,000	.8319	1.6634	3.3275
1,400,000	.8781	1.7561	3.5122
1,450,000	.9289	1.8577	3.7154

shown that the output elasticity of effort is significantly different from one, and output elasticity of stock is not significantly different from one. In other words, the production function of North Carolina hard clam fishery exhibits decreasing returns to scale with respect to fishing effort and constant returns to scale with respect to fish stock. These results are similar to Smith's findings in the lobster fishery. The estimated maximum sustainable yield is not significantly different from two million pounds of meat per annum. This result may be underestimated because it is based on the past 20 years' catch-effort data, and the resource was not fully exploited until recent years.

The North Carolina ex-vessel hard clam market is also analyzed. The results of the flexibility analysis are reasonable in magnitude and sign. The U.S. real disposable personal income (per capita) appears to have the most significant influence in determining North Carolina hard clam prices. Hard clam landings from other states, which are close substitutes for North Carolina hard clams, also have moderate influence on the North Carolina hard clam price; while landings from soft and surf clams have little effect.

The recent peak landing of 1.7 million pounds of clam meat suggests that the biological overfishing problem is not serious yet. But by contrasting the empirical supply curve with the steady-state supply curve it is evident that economic overfishing has occurred in the past and has been a serious problem in recent years. The results also show that if the number of licenses issued for hand rakes were kept at its average (468), the predicted harvest rate would be slightly less than the optimal harvest rate. Hence recent economic overfishing would have been lessened. This result confirms what fishery service officers suspected: the growing proportion of part-time fishermen using hand gear may have an adverse effect on the North Carolina hard clam fishery.

Suggestion for Further Research

The conclusions presented in the previous section are based on a biomass model employed as a result of a limited information. To derive a more applicable management policy, the data acquisition system must be set up for closer monitoring. Data such as fishing effort and cost information are important for management purposes but are not yet available. Given differences in market prices for different size clams, sampling of the size distribution of landing through the season would also be useful.

In addition, the multiple cohort model is more appropriate for examining the hard clam overfishing problem. In application, the required biological parameters such as age-specific fecundity rates, age-specific survival rates and carrying capacity are not available in the existing literature. It is suggested that future biological research should focus on providing these parameters.

Incorporating uncertainty into the model is another aspect that would be useful. Theoretical models with multi-variables (such as the multi-cohort model) under uncertainty have been developed. But they are seldom found in applications due to the 'curse of dimensionality,' or the difficulty in solving and data requirements imposed.

REFERENCES

Allen, K.R., Some Properties of the Schaefer model for Baleen Whales, Int'l. Whal. Comm. Scientific Committee Report 27:180-196 (1976).

Allen, R.L. and Basasibwaki, P., Properties of Age Structured Models for Fish Populations, J. Fish. Res. Board Can., 3:1119-1125 (1974).

Altobello, M., Optimal Control Theory As Applied to the Management of A Replenishable Natural Resource: The Atlantic Sea Scallop. Ph.D. dissertation, University of Massachusetts. 1976.

Andersen, P., Commercial Fisheries Under Price Uncertainty, J. Environ. Econ. and Manage., 9:11-28 (1982).

Anderson, L., Analysis of Open-Access Commercial Exploitation and Maximum Economic Yield in Biological and Technologically Interdependent Fisheries, J. Fish. Res. Bd. Canada. 32-1825-1842 (1975).

--------, Economic Impacts of Extended Fisheries Jurisdiction. Ann Arbor, Ann Arbor Science Publishers Inc. 1977.

Anon., Int. Whal. Comm., Scientific Committee Report, 27:1-35 (1976).

Arrow, K.J. and Intriligator, M.D., Handbooks in Economics, Book I, North-Holland Publishing Company, Amsterdam, New York, Oxford 1981.

Austin, H.M., and Haven, D.S., A Report on the Operation of A Hydraulic Escalator Dredge on Private Ground on Hampton Flats, James River, during October 1980. Marine Resources Report No. 81-3, Virginia Institute of Marine Science, Gloucester Point, VA 20pp 1981.

Bard, Y., Nonlinear Parameter Estimation, New York: Academic Press 1974.

Beal, Brian Fairfield, Effects of Environment, Intraspecific Density, Predation by Snapping Shrimp and Other Consumers on the Population Biology of Mercenaria Mercenaria near Beaufort, North Carolina. Master Thesis, UNC-Chapel Hill 1983.

Beddington, J.R., On the Dynamics of Sei Whales under Exploitation, Int. Whal. Comm., Scientific Committee Report 28, to appear.

Beddington, J.R., Watts, C.M.K., and Wright, W.D.C., Optimal Cropping of Self-reproducible Natural Resources, Econometrica 43, No. 4, 789-802, 1975.

Beddington, J.R. and Taylor, D.B., Optimum Age Specific Harvesting of a Population, Biometrics, 29: 801-809 (1973).

Beddington, J.R. and May, R.M., Harvesting Natural Populations in a Randomly Fluctuating Environment, Science 197: 463-465 (1977).

Bell, F.W., Technological Externalities and Common Property Resources: An Empirical Study of the U.S. Northern Lobster Fishery, J. Pol. Econ. 148-158 (1972).

Beverton, R.J. and Holt, S.J., On the Dynamics of Exploited Fish Populations, Fish. Invest. Lond. Ser. 2 No. 19, p. 533, 1957.

Botsford, L.W. and Wickham, D.E., Behavior of Age-Specific Density-Dependent Models and the Northern California Dungeness Crab (Cancer Magister) Fishery, J. Fish. Res. Board Can., 35:833-834 (1978).

Bradley, P.G., Some Seasonal Models of the Fishing Industry, In Economics of Fisheries Management: A Symposium, ed. Anthony D. Scott. Vancouver: Institute of Animal Resource Ecology, University of British Columbia, 1970.

Bricelj, V.M., Fecundity and Related Aspects of Hard Clam (Mercenaria Mercenaria) Reproduction in the Great South Bay, New York. M.S. Thesis, Marine Environmental Science Program SUNY at Stony Brook 1979.

Brown, G., An Optimal Program for Managing Common Property Resources with Congestion Externalities, Journal of Political Economy, Vol. 82, No. 1, January/February, pp. 163-173, 1974.

Bureau of Commercial Fisheries, U.S. Dept. of Interior, 1960-1969 North Carolina Landings, Annual Summaries, U.S. Government Printing Office, Washington, D.C.

Burt, O.R., and Cummings, R.G., Production and Investment in Natural Resource Industries, American Economic Review 60, No. 4: 576-590, 1970.

Burt, O.R., and Cummings, R.G., Natural Resource Management, the Steady State, and Approximately Optimal Decision Rules, Land Economics, 53(1), pp. 22, February, 1977.

Capps, O., Jr., Shabman, L., and Brown, J.W., Hard Clam Demand: Past Determints and Future Prospects, draft prepared for Clam Mariculture in North American, May 25, 1984.

Carriker, M.R., Biology and Propagation of Young Hard Clams, Mercenaria, Mercenaria, J. Elisha Mitchell Scientific Society 72: 57-60 (1956).

Cessine, R.S., and Strand, I.E., The Surf Clam As A Nonrenewable Resource. Maryland Agricultural Experimental Station, March 1978.

Clark, C., Profit Maximization and the Extinction of Animal Species. Journal of Political Economy, Vol. 81, No. 4, pp. 950-61, July 1973.

Clark, C.W., Mathematical Bioeconomics: The Optimal Management of Renewable Resources, New York, John Wiley & Sons. 1976.

Clark, C.W., A Delay-recruitment Model of Population Dynamics with Application to Baleen Whale Populations, J. Math. Biol. 3:381-391, 1976.

Clark, C.W., Toward a Predictive Model for the Economic Regulation of Commercial Fisheries. Canadian Journal of Fisheries and Aquatic Science, 37: 1111-1129 1980.

Conrad, J.M., Price of Hard Clams in Fulton Market, working paper, Dept. of Agriculture Economics, Cornell University, Ithaca, New York, pp. 14, 1980.

Conrad, J.M., Management of a Multiple Cohort Fishery: The Hard Clam Resource in Great South Bay, unpublished manuscript, Cornell University, 1981.

------------, Management of a Multiple Cohort Fishery: The Hard Clam in Great South Bay, AJAE 64: 463-474 (1982).

Conrad, J.M., and Castro, J.M., Bioeconomics and the Harvest of Two Competing Species, Cornell Agricultural Economics Staff Paper No. 83-8, May 1983.

Copes, C., The Backward-Bending Supply Curve of the Fishery Industry, Scot. J. Pol. Econ. 17, 69-77 (1970).

Crutchfield, J.A., and Zellner, A., Economic Aspects of the Pacific Halibut Fishery, Fishery Industrial Research I, U.S. Dept. of the Interior, Washington, 1962.

Cushing, D.H., The Variability of a Yield Curve Calculated from A Stock and Recruitment Relationship, ICES Document CM 1973/F:29, pp. 5, 1973.

Davis, H.C., Survival and Growth of Clam and Oyster Larvae at Different Salinities, Biological Bulletin, 114L: 296-307 (1958).

Davis, H.C., and Chanley, P.E., Spawning and Egg Production of Oysters and Clams, Biological Bulletin, 110: 117-128 (1956).

Deriso, R.B., Harvesting Strategies and Parameter Estimation for an Age-Structured Model. Can. J. Fish. and Aquatic Sciences. 37: 268-282 (1980).

Doi, T.A., Theoretical Treatment of the Reproductive Relationship between Recruitment and Adult Stock, Rapp. Proc.-Verb. Cons. Int. Explor. Mer. 164:14-349, 1973.

Dudley, N., and Waugh, G., Exploitation of a Single-Cohort Fishery Under Risk: A Simulation Optimization Approach, E, Environ. Econ. and Manage., 7:234-255 (1980).

Edwards, B.K., Optimal Control in Multispecies Fisheries with Interacting Populations, Dept. of Economics, Univ. of California, San Diego, La Jolla, CA 92093 and National Marine Fisheries Science Southwest Fisheries Center, PO Box 271, La Jolla, CA 92038, Nov. 25, 1983.

Eldridge, P.J., Eversole, A.G., and Whetson, J.M., Comparative Survival and Growth Rates of the Hard Clam, Mercenaria Mercenaria, Planted in Trays Subtidally and Intertidally at Varying Densities in a South Carolina Esturary, Proceedings of the National Shellfisheries Association, 69: 30-39 (1979).

Fricke, P.H., Socioeconomic Aspects of the Bay Scallop Fishery in Carteret County, North Carolina, Working Paper 81-12, UNC Sea Grant College Program, Raleigh, North Carolina, 1981.

Garrod, D.J., and Jones, B.W., Stock and Recruitment Relationship in the Northeast Arctic Cod Stock and The Implications for Management of the Stock, J. Cons. Int. Explor. Mer. 36:35-41, 1974.

Gorden, H.S., Economic Theory of a Common Property Resource: The Fishery, J. of Political Economy, 62:124-42, April 1954.

Graham, M., Modern Theory of Exploiting a Fishery and Application to North Sea Trawling, Cons. Int. Explor. Mer. 10:264-274, 1935.

Guthrie, J.F., and Lewis, C.W., The Clam-Kicking Fishery of North Carolina Marine Fisheries Review 44(1), 16-21 (1982).

Holliday, R.G., and Doubleday, W.G., Catch and Effort Trends for the Fin Fish Resources of the Scotian Shelf and Estimates of the Maximum Sustainable Yield of Groundfish (except Silver Hake), Int. Comm. Northw. Atlant. Fish. Sel. Pap 1:117-128, 1976.

Hilborn, R., Optimal Exploitation of Multiple Stocks by a Common Fishery: A New Methodology, J. Fish. Res. Board Can., 33: 1-5 (1976).

Horwood, J.W., Knights, B.J., and Overy, R.W., Preliminary Results of An Investigation into the Effects of Harvesting Whales in a Stochastic Environment, to appear.

Kamien, M.F., and Schwartz, N.L., Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management. New York, North Holland, 1979.

Keck, R., Maurer, D., and Malouf, R., Factors Influencing the Setting Behavior of Larval Hard Clams, Mercenaria Mercenaria, Proceedings of the National Shellfisheries Association, 64:59-67 (1974).

Kellogg, R.L., and Spitsbergen, D., Predictive Growth Model for the Meat Weight (Adductor Muscle) of Bay Scallops in North Carolina, Working Paper 83-6, UNC Sea Grant College Program, North Carolina State University, pp. 44.

Kellogg, R.L., A Bioeconomic Model for Determining the Optimal Timing of Harvest with Application to Two North Carolina Fisheries, Ph.D. Dissertation, N.C. State University at Raleigh, 1985.

Kennedy, V.S., Roosenbury, WH., Castagna, M., and Mihursky, J.A., Temperature-Time Relationships for Survival of Embryos and Larvae, Fish. Bulletin, 27: 1160-1168 (1974).

Krebs, C.J., Ecology: The Experimental Analysis of Distribution and Abundance, Harper and Row, New York, 1972.

Kvaternik, A., DuPaul, W., and Murray, T., Price Flexibility Analysis of Virginia Hard Clams: Economic Considerations for Management of the Fishery. Special Report in Applied Marine Science and Ocean Engineering No. 266, pp. 53, 1983.

Lampe, H.E., 'The Interaction Between Two Fish Populations and Their Market--A Preliminary Report', In Recent Developments and Research in Marine Fisheries, Bell and Hazelton, Eds., Dobbs Ferry, New York: Oceana Publications 1967.

Lefkovitch, L.P., A Theoretical Evaluation of Population Growth After Removing Individuals from Some Age Groups, Bull. Ent. Res. 57:437-445 (1967).

Leslie, P.H., On the Use of Matrices in Certain Population Mathematics, Biometrika, 35: 183-212 (1945).

Lett, P.F., and Benjaminsen, T., A Stochastic Model for the Management of the Northwestern Atlantic Harp Seal Population, J. Fish. Res. Board Comm. 34: 1155-1187, 1977.

Lett, P.F., and Doubleday, W.G., The Influence of Fluctuations in Recruitment on Fisheries Management Strategy with Special Reference to Southern Gulf of St. Lawrence Cod, Int. Comm. Northw. Atlant. Fish. Pap. 1:171-193, 1976.

Lett, P.F., and Kohler, A.C., Recruitment: A Problem of Multispecies Interaction and Environmental Perturbations with Special Reference to Gulf of St. Lawrence Atlantic Herring, J. Fish. Res. Board Can. 33: 1353-1371, 1976.

Lewis, E.G., On the Generation and Growth of Populations, Sankhya, 6:93-96 (1942).

Lewis, T.R., Optimal Resource Management Under Conditions of Uncertainty: The Case of an Ocean Fishery, Ph.D. dissertation, University of California, San Diego 1975.

Lewis, T.R., Exploitation of a Renewable Resource Under Uncertainty, Can. J.Econ. 14(3) pp. 422-439, Aug. 1981.

Lotka, A.J., Elements of Physical Biology, Williams & Wilkins, Baltimore, 1925.

MacPhail, J.S., A Hydraulic Escalator Shellfish Harvester Fisheries Research Board of Canada Bulletin No. 128, pp. 1-24 (1961).

Maiolo, J., and Tschetter, P., Social and Economic Impacts of Coastal Zone D, University of North Carolina Sea Grant College Program, Summer 1983.

May, R. M., Simple Mathematical Models with Very Complicated Dynamics, Nature, 261: 459-467, 1976.

May, R.M., Beddington, J.R., Horwood, J.W., and Shephard, J.G., Exploiting Natural Populations in an Uncertain World, Math. Biosciences, 42: 219-252 (1978).

Mays, R.K., and Miller, D.S., A Preliminary Assessment of the Redfish (Sebastes Marinus) in ICNAF Divisions 4VWX, Int. Comm. Northw. Atlant. Fis. Sel. Pap. 1:31-39, 1976.

Mendelssohn, R., Optimal Harvesting Strategies for Stochastic Single-Species, Multiage Class Models, Math. Biosciences, 41: 159-174 (1978).

----------, Determining the Best Trade-off Between Expected Economic Return and the Risk of Undesirable Events When Managing a Randomly Varying Population, J. Fish. Res. Board Can., 36: 939-947 (1979).

----------, (a) Using Markov Decision Models and Related Techniques for Purposes Other Than Simple Optimization: Analyzing the Consequences of Policy Alternatives on the Management of Salmon Runs, Fish. Bulletin, 78: 35-50 (1980).

----------, (b) A Systematic Approach to Determining Mean-Variance Tradeoffs When Managing Randomly Varying Populations, Math. Biosciences, 50: 75-84 (1980).

Neher, P., Notes on the Volterra-Quadratic Fishery, Journal of Economic Theory, 6: 39-49, May 1974.

N.C. Dept. of Natural Resources and Community 1980-82 North Carolina landings.

Pella, J.J., and Tomlinson, P.K., A Generalized Stock Production Model, Int. Amer. Trop. Tuna Comm. Bull. 13: 421-496, 1969.

Perrin, R.K., and Johnson, T., Linear Programming and Optimal Control: An Introduction to Optimizing Procedures in Economics. Economics Information Report No. 54, North Carolina State University at Raleigh, 1978.

Peterson, C.H., Clam Predation by Whelks (Busycon Spp.): Experimental Tests of the Importance of Prey Size, Prey Density, and Seagrass Cover, Marine Biology 66: 159-170, 1982.

Peterson, C.H., Summerson, H.C., and Fegley, S.R., The Relative Efficiency of Two Clam Rakes and Their Contrasting Impacts On Seagrass Biomass, Univ. of North Carolina at Chapel Hill, Fish. Bull. 81: 429-434, 1983.

Pinhorm, A.T., Catch and Effort Relationships of the Groundfish Resource in ICNAF Subareas 2 and 3, Int. Comm. Northw. Atlant. Sel. Pap. 1: 107-115, 1971.

Plourde, C.G., A Simple Model of Replenishable Resource Exploitation, Amer. Econ. J. 9:256-266, 1971.

Pope, J.G., The Application of Mixed Fisheries Theory to the Cod and Redfish Stock of Subarea 2 and Division 3K, Int. Comm. Northw. Atlant. Fish. Sel. Pap. 1:163-169, 1976.

Quirk, J., and Smith, V., Dynamic Models of Fishing, in A. Schott, ed., Proceedings of the H.R. MacMillan Fisheries Symposium, Vancouver, 1969.

Reed, W.J., A Stochastic Model for the Economic Management of a Renewable Animal Resource, Math. Biosciences, 22: 313-337 (1974).

----------, The Steady State of a Stochastic Harvesting Model, Math. Bioschiences 41: 273-307 (1978).

----------, Optimum Age-Specific Harvesting in a Nonlinear Population Model Biometrics 36: 579-593 (1980).

Ricker, W.D., Computation and Interpretation of Biological Statistics of Fish Populations (pp. 382), Fish. Res. Board. Can. Bull., 191 (1975).

Ricker, W.E., Critical Statistics from Two Reporduction Curves, Rapp. Proc -Verb. Cons. Int. Explor. Mer. 164: 333-340, 1973.

Rorres, C., and Fair, W., Optimal Harvesting Policy for An Age-Specific Population, Math. Biosciences, 24: 31-47 (1975).

Ruppert, D., Reish, R.L., Deriso, R.B., and Carroll, R.J., Optimization Using Stochastic Approximation and Monte Carlo Simulation With Application to Harvesting of Atlantic Menhaden, Unpublished paper, 1983.

-----------, Report of Research During Phase II of the Biological Simulation Model for Atlantic Menhaden, Curriculum in Marine Sciences, University of North Carolina at Chapel Hill, pp. 127,. 1981.

-----------, A Stochastic Model for Managing Atlantic Menhaden and Assessing Managerial Risks, Institute of Statistics Mineo Series No. 1532, Department of Statistics, University of North Carolina at Chapel Hill, 1983.

Schaefer, M.B., Some Aspects of the Dynamics of Populations Important to the Management of the Commercial Fish Populations, Inter. Amer. Trop. Tuna Comm. Bull. 1:26-56, 1954.

Schaefer, M.B., Some Considerations of Population Dynamics and Economics in Relation to the Management of Marine Fisheries, J. of the Fisheries Research Board of Canada, 14: 669-681, 1957.

Smith, J.B., Replenishable Resource Management Under Uncertainty: A Re-examination of the U.S. Northern Fishery., J. Environ. Econ. and Manage. 7:209-219 (1980).

Smith, V., Economics of Production from Natural Resources, American Economic Review, 58 (3): 409-431, 1968.

Smith, V., On Models of Commercial Fishing, J. of Political Economy, pp. 181-198, Feb. 1969.

Smith, V., General Equation with a Replenishable Natural Resource, The Review of Economic Studies, Symposium on the Economics of Exhaustible Resources, pp. 105-115, 1974.

Spence, M., Blue Whales and Applied Control Theory, Technical Report No. 108, Stanford University, Institute for Mathematical Studies in Social Science, 1973.

Strand, I., An Economic Appraisal of Eastern Shore Seafood Harvesting, Mar. Res. Adv. No. 11, Virginia Institute of Marine Science, Gloucester Point, VA, pp. 6, 1976.

Street, M.W., Comprehensive Report on the Hard Clam (Mercenaria Mercenaria) Industry in North Carolina, unpublished paper 1976.

------------, A Look at the 1980 Catch and Trends in North Carolina's Seafood Catch Down, Tar Heel Coast 16(2) 1981.

------------, The 1981 Trend, Trends Past 17 Years, 1981 North Carolina Seafood Catch Down, Tar Heel Coast 17(2) 1982.

------------, The 1982 Trend, Trends Past 18 Years, A Look At The 1982 Commercial Catch, Tar Heel Coast 18(2) 1983.

Tiller, R.E., Glude, J.B., and Stringer, L.D., Hard Clam Fishery of the Atlantic Coast Commercial Fisheries Review 14(10) pp. 25, 1952.

Tomek, W.G., Robinson, R.L., Agricultural Product Prices, Cornell University Press. Ithaca, N.Y. pp. 376, 1972.

Turvey, R., Optimization in Fishery Regulation, American Economic Review, 54:64-76, March 1964.

U.S. Dept. of Commerce 1970-1979 Current Fisheries Statistics: North Carolina Landings, Annual Summary, National Marine Services, National Ocean and Atmospheric Administration, Washington, D.C.

------------, Historical Statistics of the United States Colonial Times to 1970 Bicentennial Edition. Part 1, E 135-166.

------------, Shellfish Market Review and Outlook, 1974-1982, National Ocean and Atmospheric Administration, Washington, D.C.

------------, Statistical Abstract of the United States, 102 ed. National Data Bank and Guide to Sources. pp. 468.

------------, Statistical Digest - Fishery Statistics of the United States, National Marine Fisheries Service, 1961-67.

------------, Fishery Statistics of the United States, National Marine Fisheries Service, 1968-76.

------------, Survey of Current Business, Table 1, Bureau of Economic Analysis, August 1983.

------------, Survey of Current Business, Table 4, Bureau of Economic Analysis, August 1982.

U.S. Dept. of The Interior, Fish and Wildlife Service, Statistical Digest, Fishery Statistics of The United States, 1955-67.

Wallace, T.D., Pretest Estimation in Regression: A Survey, Amer. J. Agr. Econ. pp. 431-443 (1977).

Walters, C.J., Optimal Harvest Strategies for Salmon in Relation to Environment Variability and Uncertain Production Parameters. J. Fish. Res. Board Can. 32: 1777-1784 (1975).

-----------, Some Dynamic Programming Applications in Fisheries Management 233-246 in Dynamic Programming and Its Applications by Martin L. Puterman 1977.

-----------, and Hilborn R., Ecological Optimization and Adaptive Management, Ann. Rev. Ecol. Syst., 9:157-88 (1978).

Waters, J.R., Economic Analysis of the Pink Shrimp Discard Problem in Pamlico Sound, Ph.D. dissertation, North Carolina State University at Raleigh, 1983.

Wasan, M.T., Stochastic Approximation, Cambridge at the University Press Cambridge Tracts in Mathematics and Mathematical Physics, No. 58, 1969.

Wells, H.W., Abundance of the Hard Clam Mercenaria Mercenaria in Relation to Environmental Factors, Ecology, 38: 123-128 (1957).

Wilson, J.A., The Economical Management of Multiple-Species Fisheries, Land Economics 58(4): 417-34 (1982).