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EFFECTS OF LIMITED ACCESS MANAGEMENT ON SUBSTITUTABLE RESOURCES: A CASE STUDY OF THE SURF CLAM AND OCEAN QUAHOG FISHERY*

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ABSTRACT

The tragedy of the commons and joint markets for natural resources present researchers with intriguing questions: What policies efficiently protect both primary and substitute resources? Why do some management policies produce counter-intuitive results? Fishery management is one example of regulating complex economic and ecological systems and provides case studies of policies used to correct the inefficiencies inherent in common property resources. Using the Mid-Atlantic surf clam and ocean quahog fishery as an example, this article models the effects of limited access policies on substitutable natural resources. The history of the surf clam and ocean quahog fishery illustrates the difficulties of managing common property and substitutable resources. The fishery is a complex system in which economic, ecological, and regulatory factors affect harvesting decisions for two substitutable resources. I model the profit-maximizing decisions made by individual vessel owners and illustrate how biological and economic parameters affect these closely linked clam populations. Using this model I simulate harvest patterns and populations of the two species under limited access management.

INTRODUCTION

A classic example of a common property is the ocean. There are no visible boundaries, and our society traditionally considers the ocean to be public property. In addition to being price takers, fishers may also be considered to be population takers. Given the structure of the common property each fisher must take the

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population of the resource as a given. Costs of conservation are borne by the individual while benefits are distributed among all participants. The results are dissipation of the scarcity rent and economic inefficiencies.

An additional difficulty exists when there are substitutes for the natural resources. An example is the rain forest. The lumber market is satisfied by wood regardless of the country of origin. If the supply from one country is reduced by strict legislation, the demand may be met by an increase in harvesting in an adjacent country. The total loss may be greater than if there had been similar management regimes. The problems of displacement of effort are also apparent in wildlife management; for instance, the regulation of ivory trade.

The incentive structure inherent in common property leads to environmental degradation and economic inefficiencies. In the absence of regulation of these natural resources, overexploitation may destroy future benefits. A cursory review of resource management, however, reveals a plethora of examples of policies with undesired results. One example is the halibut fishery which is well known for its extremely limited number of allowed fishing hours. Its nickname "the halibut derby" reflects the recklessness exhibited in the fishery, resulting in accidents, inefficient use of capital and labor, and a boom and bust supply cycle. These examples demonstrate that an understanding of the dynamics of natural resource usage under alternative management regimes is essential to reducing these inefficiencies.

A common fishery management technique is limited access, but might this technique actually increase inefficiency and displace excess effort to a substitute? To explore this question, this article simulates the general equilibria of the surf clam and ocean quahog fishery under limited access. This fishery experienced the first federal level implementation of limited access in the United States and therefore provides evidence of its long term effects.

The next section provides a brief introduction to the surf clam and quahog fishery. Part two builds the profit and production functions which drive harvesting decisions. The biological constraints are discussed and incorporated into the model in part three. Results of the price regressions and simulations are presented in the fourth part, and part five examines the robustness of the model. An appendix details the estimation of the price function and parameters.

PART ONE: THE SURF CLAM AND OCEAN QUAHOG FISHERIES

Commercial concentrations of surf clams and quahogs are found primarily in the Mid-Atlantic states, and their harvesting similarities are striking. Currently, the same vessels, equipment and crew may be used to harvest either species; however, harvesting did not always encompass both species. The most important difference between the two ventures is the additional travel time necessary to reach the deeper water required for quahog beds. The strong vessels needed to harvest in the deeper waters did not exist in the early fishery (started in 1870 as a bait fishery). Additionally, the low quality of the quahog meat (its gray tint and stronger taste) severely reduced its demand. Effort was therefore directed primarily at the easily processed surf clam.

As more vessels entered the industry, the surf clam population exhibited decreased marginal returns and increased marginal costs, implying overharvesting. In 1976, anoxic conditions off the coast of New Jersey destroyed approximately 70 percent of the remaining population [1]. This crisis compelled implementation of conservation management and establishment of a regulatory body, the Mid-Atlantic Fishery Council.

While the management regime included provisions for both species, those directed toward quahogs were never enacted. The reduction of allowable harvests of surf clams by a moratorium on new entry, fishery quotas, and restricted fishing time (the management plans for 1976-1990), increased the pressure to use quahogs.

The increase in price per bushel of surf clams and technological innovation created a market and harvest abilities for quahog meat. Figure 1 shows the dramatic increase in quahog harvest while surf clam harvest decreased in the period 1975-1983. Figure 2 illustrates the continued increase in quahog harvest and the inverse relationship between the quantity of surf clams and quahogs harvested [2].

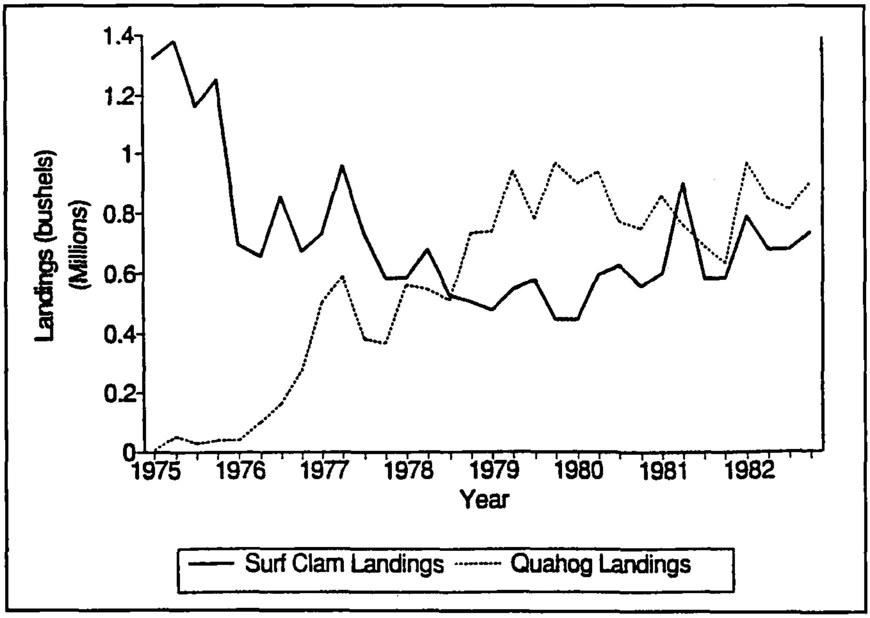

Figure 1. Surf Clam and Quahog Landings (1975-82).

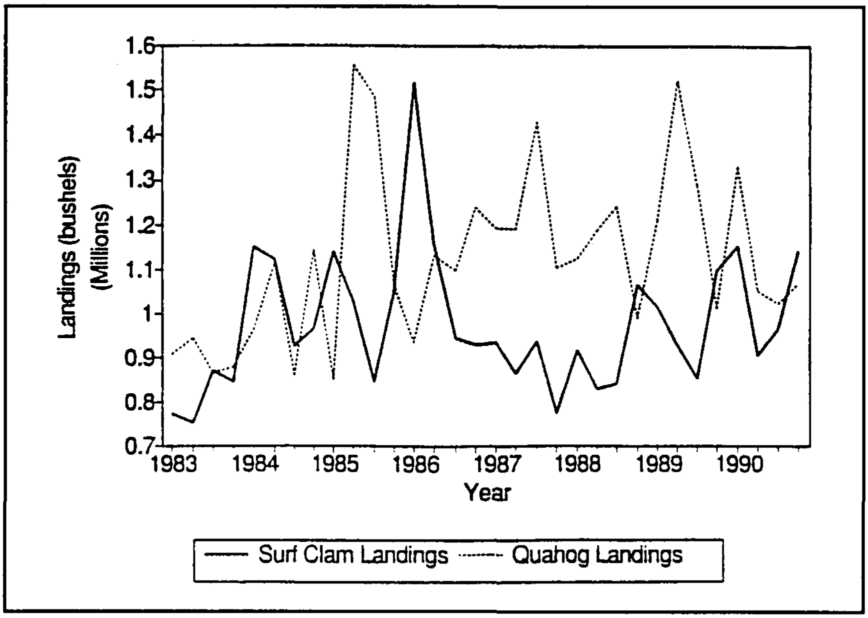

Figure 2. Surf Clam and Quahog Landings (1983-90).

The biological properties of the quahog population makes this rapid increase in harvesting of great concern. The majority of the quahog population is greater than one hundred years old and was spawned twenty to one hundred years ago [3], and no new recruitment has ever been detected [2]. The displacement of harvesting pressure to this extremely slow growing and delicate resource leaves it vulnerable to over-exploitation and the destruction of future resource benefits. The fishery's history dramatically presents two questions: does regulation of one resource displace excess effort to substitutable resources, and is limited access an efficient management policy?

The rapid increase in quahog extraction highlights a crucial issue. Has the regulation and the consequential price increase for one resource, the surf clam, displaced the problem of overfishing onto the substitute population? This issue is crucial not only to this particular fishery but to many others as well. A similar case is the New England ground fishery where many species inhabit the same territory. A poignant joke in the industry is, "The New England groundfish industry in crisis! Again." Is management doomed to continue the cycle of overharvesting by displacing one fishery's problem to another fishery?

Appropriate policies for substitutable resources are crucial to the fishery industry as well as to other natural resource management debates. An analogous case scenario is that of groundwater supply. If one region implements a strict management plan, what will occur in a neighboring region with less restrictive laws? Will the result be more detrimental than if both regions had similar management policies? What are the consequences if the substitute resource regenerates at a slower rate than the primary? This article explores the question of displacement of effort due to limited access policies.

Finally, this article will address the classic question of resource management. Is limited access through restricting fishing days or trips an efficient scheme? What happens to the supply, prices and populations of the two species as the number of days fished is reduced? Are boom and bust cycles reflective of short-run versus long-run implications? In the short-run is effort displaced to a substitute which in the long-run cannot maintain the excess exploitation? Are these outcomes inherent in limited access policies?

PART TWO: THE OPTIMIZATION QUESTION

This section develops a model of short-run individual vessel allocation to illustrate the impact of limited access policies on the harvest patterns. In the short-run analysis the amount of harvesting effort is endogenous to the model, but there is neither entry nor exit of fishing vessels. Given the economic and biological conditions at one point in time, how does a fisher decide which species to harvest? By modeling this decision making process we may address the larger issue of the effects limited access policies exert on production and prices (see Table 1).

Table 1. Variables and Definitions Used in this Article

subscript q	Denotes quahogs
subscript c	Denotes surf clams
π	Profit
Q_i	Quantity of surf clams and quahogs harvested (i = c, q)
P_i	Prices of surf clams and quahogs (i = c,q) ($ per bushel)
K, L	Quantity of capital and labor
r,w	Costs of capital and labor
α,β	Returns to capital and labor
T_i	Time spent harvesting each species (i = c,q)
g	Parameter to reflect decreasing marginal returns to time
D	Total fishable time (where some days are not fishable due to weather, equipment failure, and other factors)
A_i	Abundance parameter (i = c,q)
v	Environmental carrying capacity for quahogs
y	Population growth rate of quahogs
c	Environmental carrying capacity for surf clams
s	Population growth rate for surf clams

Production Functions

The Cobb-Douglas production function has been suggested for this industry [4]. I employ this production function in my analysis. In addition to capital vessel and equipment, represented by (K) and labor (L) the production function incorporates time (T) and abundance (A) parameters. The time parameter (T) and constraint on allowable fishable days (D) incorporate the effects of the management regimes.

A decision to harvest surf clams or quahogs is reversible after each trip; therefore, the annual profit function should allow harvesting to alternate between both populations throughout the year.

The total quantities of quahogs and surf clams harvested are:

$$Q_q = T_q g\ A_q\ K^{\alpha}\ L^{\beta} \tag{1a}$$

$$Q_c = [D - T_q]^g\ A_c\ K^{\alpha}\ L^{\beta} \tag{1b}$$

The parameter A_i ($i = c, q$) reflects the relationship between the abundance of the population and the returns to fishing effort.[1] This parameter is endogenized in the model in part three. Decreasing marginal returns to time are captured by the exponent (g). It incorporates the wear of time on the crew and the vessel. In addition it reflects the decrease in biomass (decrease in parameter A_i, $i = c, q$) which decreases catch per hour. Plotting the log of hours spent fishing versus the log of the catch and estimating this function provides an estimate of the returns to time. Using this method I estimate the parameter value of g to be 0.82.

Quantities of capital and labor, their costs and their respective rates of return are assumed to be equal for the two fisheries, because the same vessel and crew are used in both ventures.[2]

Profit Function

The profit function explicitly accounts for the constraints on the allowable fishable time and incorporates the production function:

$$\pi = P_q A_q T_q g\ K^{\alpha} L^{\beta} + P_c A_c T_c g K^{\alpha} L^{\beta} - rK - wL + \lambda\ (D-T_q-T_c) \tag{2}$$

where the final term, $\lambda\ (D-T_q - T_c)$, represents the constraint on fishable days. The shadow price, lambda, represents the increase in net benefits if the allowable days fished were to increase.

Theoretically a firm would maximize the present value of a stream of profits. Then this series of decisions would be used to determine the abundance at any

[1] Note that the elasticity of harvest with respect to abundance is assumed to be one. That is, as abundance decreases the catch per unit effort is assumed to fall linearly.

[2] The values for α and β are estimated using cost share data for the fishery. To prevent a bang-bang solution and to represent the inherent decreasing returns to inputs, α and β are rounded down to 0.8 and 0.1 respectively.

time, t. This profit function, however, assumes a myopic firm that maximizes profit at each moment in time, and the implications need to be acknowledged. Primarily, the myopic function does not account for the effect of other individuals' harvests on the abundance parameter. Additionally, in this model the individual does not account for the impact of his own past harvests (note that only Q_i, ($i = c$, q) appears in the abundance parameter). For purposes of creating a model which is sufficiently tractable to solve the dynamic problem, I chose to model the myopic firm rather than attempting to incorporate an intertemporal series of profit maximizing decisions. This assumption exaggerates the tragedy of the commons scenario and therefore overestimates the externalities.

Optimal Capital and Labor

Partial derivatives of (2) yield the following first order conditions:

$$\frac{\partial \pi}{\partial T_i} = \frac{A_i P_i g K^{\alpha} L^{\beta} T_i^{\,g}}{T_i} - \lambda = 0 \qquad (3a)$$

$$(i = c, q)$$

$$\frac{\partial \pi}{\partial K} = (K^{\alpha} L^{\beta}) \frac{\alpha A_c P_c T_c^{\,g}}{K} + (K^{\alpha} L^{\beta}) \frac{\alpha A_q P_q T_q^{\,g}}{K} - r = 0 \qquad (3b)$$

$$\frac{\partial \pi}{\partial L} = (K^{\alpha} L^{\beta}) \frac{\beta A_c P_c T_c^{\,g}}{L} + (K^{\alpha} L^{\beta}) \frac{\beta A_q P_q T_q^{\,g}}{L} - w = 0 \qquad (3c)$$

$$\frac{\partial \pi}{\partial \lambda} = D - T_c - T_q = 0 \qquad (3d)$$

Solving for optimal K and L gives:

$$L\,(A_q, A_c, P_q, P_c) = \frac{w^{(1-\alpha)/(\beta 1)} * r^{(\alpha)/(\beta 1)}}{\beta^{(1-\alpha)/(\beta 1)} * \alpha^{(\alpha)/(\beta 1)} * C^{1/(\beta 1)}} \qquad (4)$$

and

$$K\,(A_q, A_c, P_q, P_c) = \frac{w^{(\beta/\beta 1)} * r^{(1/\beta 1)}}{\beta^{(\beta/\beta 1)} * \alpha^{(1-\beta)/\beta 1} * C^{(1/\beta 1)}} \qquad (5)$$

Solving for time spent in each fishery:

$$T_q(A_q, A_c, P_q, P_c) = \frac{D A_c^{\,g1} P_c^{\,g1}}{A_c^{\,g1} P_c^{\,g1} + A_q^{\,g1} P_q^{\,g1}} \qquad (6)$$

$$T_c\,(A_q,A_c,P_q,P_c) = \frac{D}{1+\dfrac{(P_cA_c)^{g1}}{(P_qA_q)^{g1}}} \tag{7}$$

Where:

$\beta = \alpha + \beta - 1$

$g1 = 1/(g-1)$

$C\,(P_q, P_c, A_q, A_c) = [P_qA_qT_qg + P_cA_cT_cg]$

PART THREE: POPULATION DYNAMICS

Thus far we have solved for time spent harvesting each species, the optimal amount of capital and labor, and the profit function. Now the dynamic question, how do the economic factors, given no change in number of vessels, affect the population of surf clams and ocean quahogs? I employ the traditional logistic growth model to incorporate the population dynamics of the fishery [5]. Though more complex population models provide very detailed explanations of fishery populations, the Schaefer model is a good approximation of the relationship between the current population and the population growth.

The parameter for abundance, A_i, may be endogenized by solving for it in terms of the variables in the population growth model. The population model is written as:

$$\frac{dX_t}{dt} = J\,X_t\left[1-\frac{X_t}{E}\right] - Q_i \tag{8}$$

$$(i = c, q) \quad (J=y, s) \quad (E = v, c)$$

where Q_i is the harvest time t, X_t is the population in time t, J is the intrinsic growth rate of the population, and E is the environmental carrying capacity.

Two main issues arise in the development of a population dynamics model. The first question is the applicability of this model, equation (8), to each particular species. Second, what is the estimate of the intrinsic population growth rate. These issues are discussed in the appendix.

The history of overharvesting and widespread destruction of the surf clam indicates that the surf clam population is not constrained by the environmental carrying capacity [6]. Therefore the proportion X/E is so small that we can ignore its second order terms to linearize the growth function. Although this assumption does not capture the non-linearity of the population's growth, this point would be a problem only if there were to be a miraculous increase in the population to its carrying capacity.

Can this assumption of unconstrained population growth be applied to the abundance model of the quahog? First, the highly adaptable feeding habits of bivalves make them resilient to resource depletion, and second, National Marine Fishery Service abundance tows indicate that room remains for quahog population expansion. These studies show no evidence of a population constraint for the quahog [7]. If the fraction of the carrying capacity for both species present is approximately zero then in equation (8) the term:

$$\frac{X}{E} \approx 0$$

and equation (8) simplifies to,

$$\frac{dX}{dt} = J\,X(t) - Q_i \tag{8b}$$

The harvest levels are a function of the species' abundance (A_i), that is, the fraction of the environmental carrying capacity actually present at time t:

$$A_i(t) = \frac{X_t}{E} \qquad \text{or } X(t) = A_i(t) * E \tag{8c}$$

Solving for the abundance parameter in terms of these variables yields:

$$A_i(E,J,Q_i,t) = \frac{Q_i}{E\,J} - \frac{\hat{e}^{\,Jt}\,(Q_i - E\,J)}{E\,J} \tag{9}$$

$$(i{=}c,\ q) \qquad (J{=}y,\ s) \qquad (E{=}v,\ c)$$

I substitute this expression (9) for all occurrences of A_i in the equations (1a) and (1b), which are the supply equations. This substitution reveals the reinforcing relationship between the market and the populations of the two resources. Harvest in the last period (as determined by the parameters) determines the abundance index and the corresponding profit maximizing decision this period. In the simulations both the abundance parameter (A_i) and harvest quantities (Q_i) are solved for simultaneously, thus representing the interactive nature of the fishery's economic and ecological aspects.

The Bioeconomic Model

To complete the model, I solved equations (4), (5), (6), (7), (9) simultaneously. Explicitly, T_q, T_c are replaced by (6) and (7), respectively. K is replaced by (5) and L by (4). Then for every occurrence of A_i ($i = c, q$), substitute its expression in terms of the biological parameters and quantity of harvest, equation (9). This substitution yields:

$$\begin{aligned} Q_q(A_q,A_c,P_q,P_c) = {} & A_q(v,y,Q_q,t) * [T_q(A_q,A_c,P_q,P_c)]^g \\ & * [K(A_q,A_c,P_q,P_c)]^{\alpha} * [L(A_q,A_c,P_q,P_c)]^{\beta} \end{aligned} \tag{10}$$

$$Q_c(A_q,A_c,P_q,P_c) = A_c(c,s,Q_c,t)*[T_q(A_q,A_c,P_q,P_c)]^g *[K(A_q,A_c,P_q,P_c)]^{\alpha} * [L(A_q,A_c,P_q,P_c)]^{\beta} \quad (11)$$

PART FOUR: SIMULATIONS OF THE MODEL

In this section simulations are presented to indicate the possible effect of limited access. The returns to time and inputs, the biological parameters for both species, and their prices were estimated using data collected about the fishery (see Appendix and Table 2).

Table 2. Parameters for Simulations

Variable	Parameter Value
g, returns to time	0.82
α, returns to capital	0.8
β, returns to labor	0.1
r, cost of capital ($)	55.89
w, cost of labor ($)	11.28
v, carrying capacity for quahogs (bu)	5.4 billion
y, quahog population growth rate	0.0002
c, carrying capacity for surf clams (bu)	1.9 billion
s, surf clam population growth rate	0.00067

Table 3. Initializing the Model

Variable	Initial Value
Qq, quahog harvest (bushels)	2 million
Qc, surf clam harvest (bushels)	5 million
Pq, initial price ($/bu) of quahogs	3.43
Pc, initial price ($/bu) of surf clams	7.57
Aq, quahog abundance parameter	0.3
Ac, surf clam abundance parameter	0.3
t, time	0

Note: There are twenty iterations of each simulation (t = 1 to 20).

Estimates were used for the starting values of endogenous variables. These estimates were also derived using data about the fishery and are described in detail in the Appendix and Table 3.

To integrate the economic factors into the model, prices for both species were endogenized. A system of simultaneous equations using three staged least squares was estimated using quarterly data from 1978 through first quarter 1986.[3] The system of equations and regression results are detailed in the Appendix. Solving for the prices of surf clams and quahogs in terms of the landings of each species gives:

$$SCp = \frac{10516542 - SCLand}{185585.94} + 0.429516\, Q_p \tag{12}$$

$$Q_p = \frac{105165.42 - QLand}{628.07246} + 429.52087\, SCp \tag{13}$$

Where Q_p is the price per bushel of quahogs, SCp is the price per bushel of surf clams, SCLand is the supply of surf clams, and QLand is the supply of quahogs.

For these simulations prices were given an initial value (the fourth quarter 1990, cost per bushel of each species) then the simulation was run. Now the abundance parameter, price, and supply for each species are determined by the model.

Results of Simulations

The complexity of the system prohibited symbolic solutions; therefore, I obtained numeric solutions (using Mathcad) to the system of four simultaneous equations (Q_i, A_i where $i = c, q$). The parameters were defined and the resulting harvests plotted.

Several questions can be answered by the simulations. First, is there always an interior solution, or could there be a corner solution? Second, what is the effect of limited access (parameter D) on harvests? Third, how robust is the model? The last question is discussed in detail in the section on sensitivity analysis in part five.

First, the results indicate that it is most profitable under all policy regimes to split fishing time between the two species. There is always an interior solution with the management regimes modeled. This result is congruent with harvesting patterns exhibited in the fishery (see Figures 1 and 2).

Next, how does changing the regulatory regime (parameter D) affect the harvest patterns? Crowding back the allowable fishable time is represented by decreasing the value of D, allowable fishable days (one trip is approximately one day). The

[3] The small number of observations obviously creates drawbacks. Primarily, it makes it difficult to reject the null hypotheses that a coefficient is significantly different from zero. However, for the purposes of these simulations, the relative prices generate meaningful results.

values of 250, 200, 150, 100, 50 and 25 were used to model different degrees of limited access.

Figures 3 and 5 show that with least restrictive limited access policies (D = 250), time harvesting is primarily directed toward surf clams. With the greatest number of fishing days, the supply of surf clams is greatest and that of quahogs the least.

As the management becomes more restrictive, D is reduced, the quantity of quahogs harvested increases and that of surf clams decreases. In other words, in more restrictive limited access regimes, more effort is directed to the substitute quahog. This result illustrates the difficulty of managing substitutable resources and emphasizes the displacement of effort even when both species are regulated (see Figures 3-6).

To gain a better idea of the forces directing the fishery, we need to look at the general market equilibria. The initial supplies and demands are illustrated by S and D in Figures 7 and 8. Given maximum fishing days, the majority of time is spent fishing the preferred surf clam. Reducing harvesting time reduces the supply of surf clams (S*). This shift in supply establishes a higher equilibrium price for surf clams (see Figure 7).

The higher price for surf clams increases the demand for quahogs (D*). Shifting the demand curve to the right, increases the price for quahogs (see Figure 8).

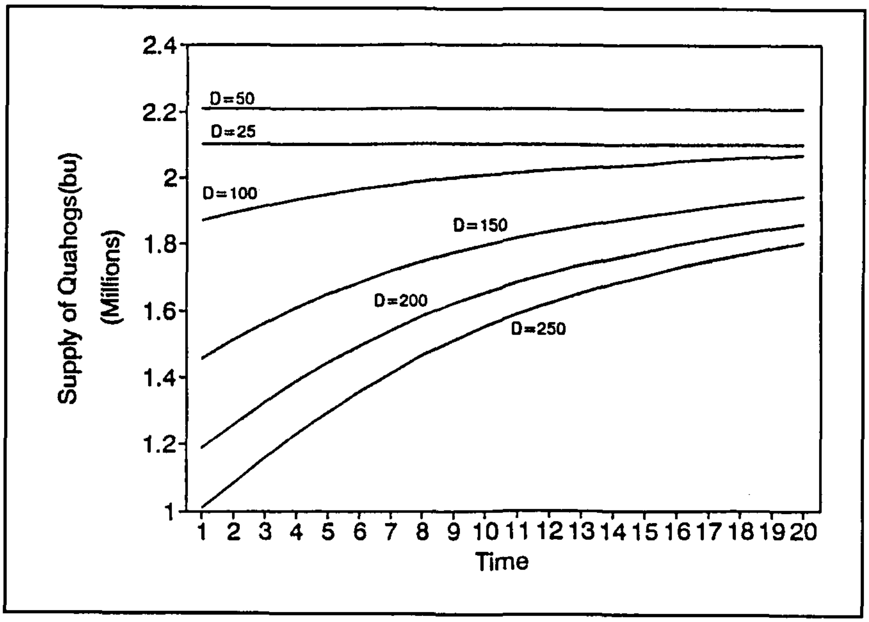

Figure 3. Supply of quahogs under limited access.

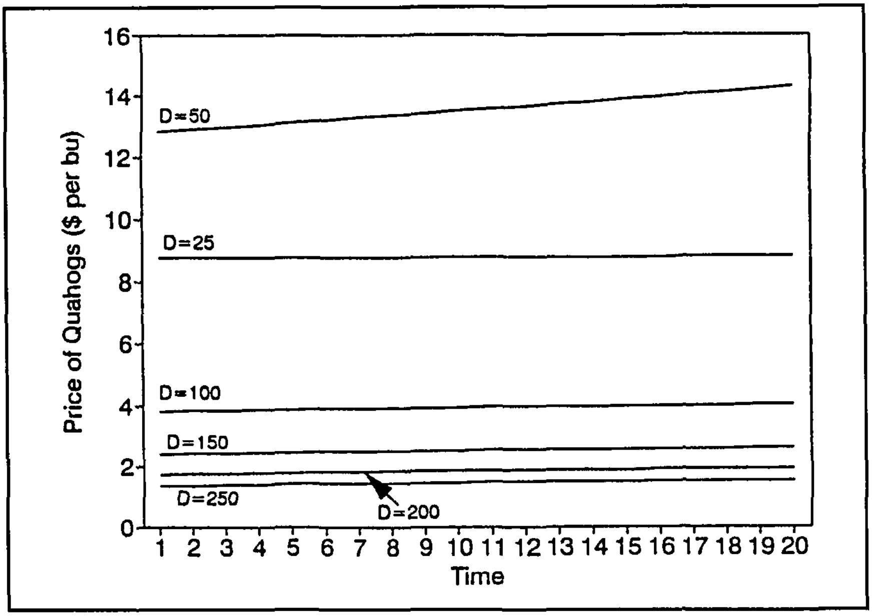

Figure 4. Price of quahogs under limited access.

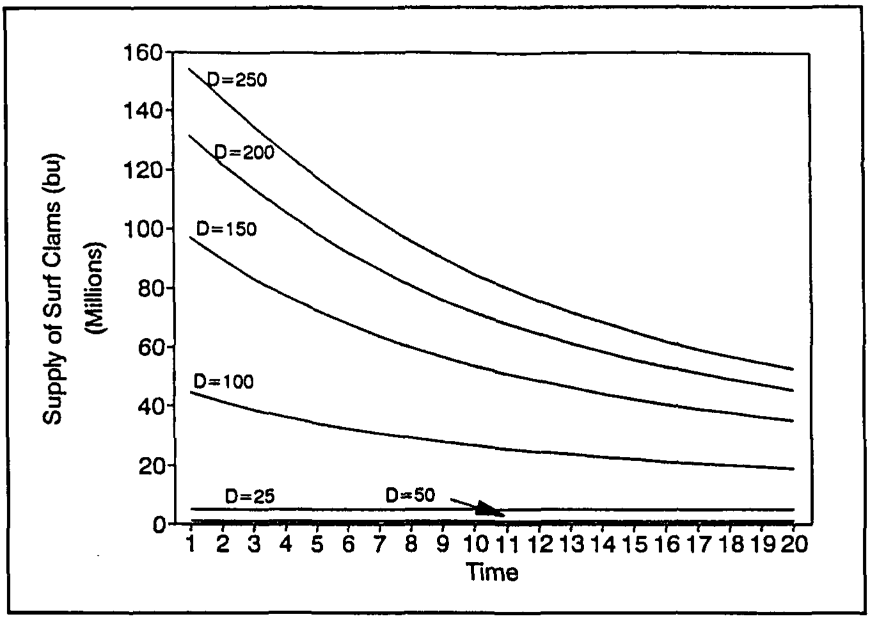

Figure 5. Supply of surf clams under limited access.

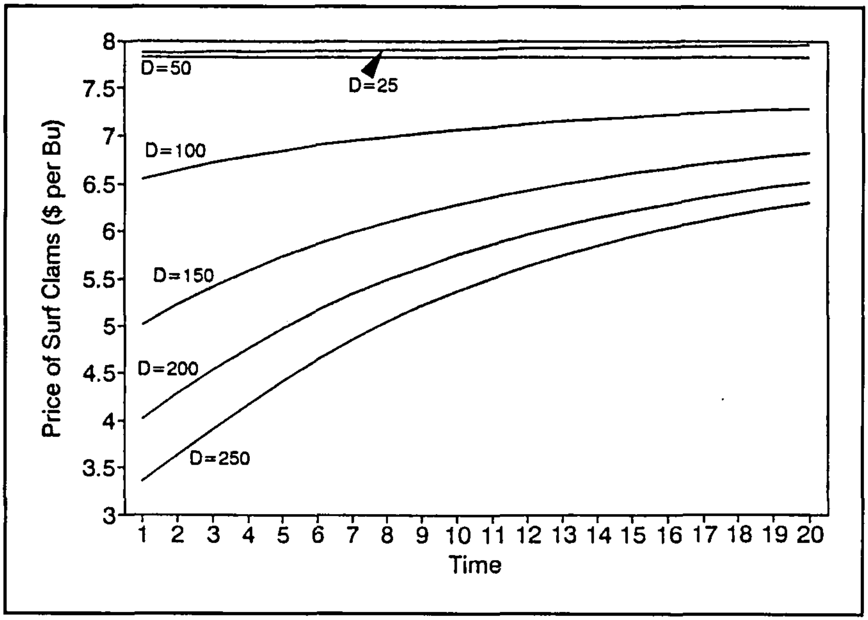

Figure 6. Price of surf clams under limited access.

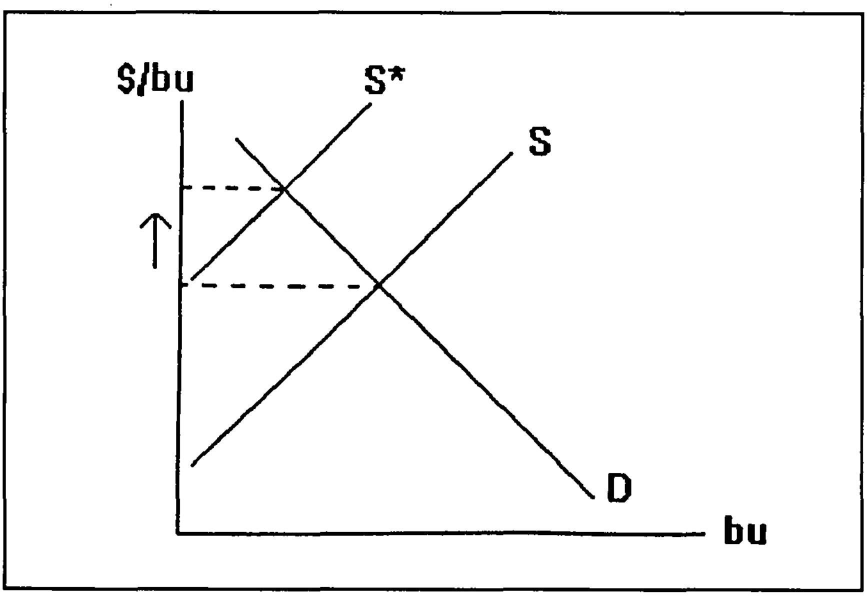

Figure 7. Market equilibrium for surf clams.

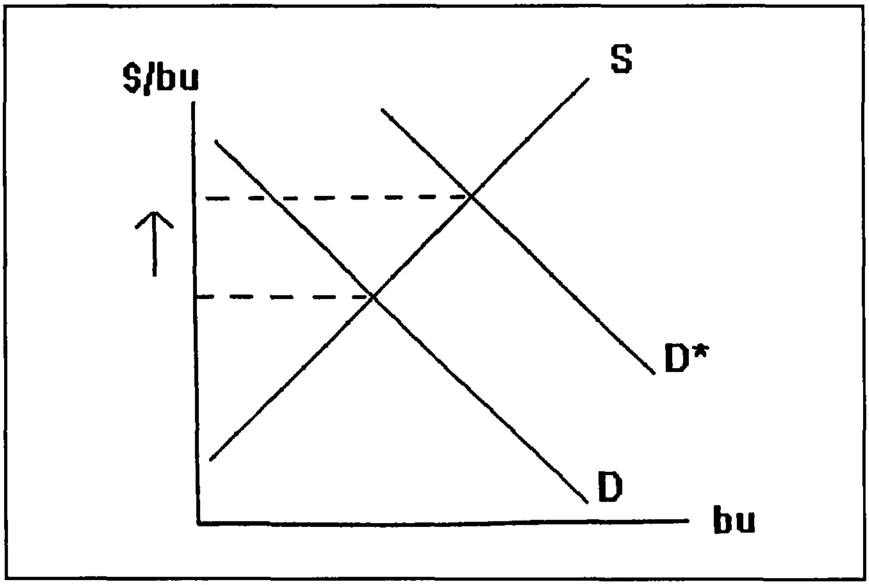

Figure 8. Market equilibrium for quahogs.

These two figures illustrate that as the policy becomes more restrictive, excess effort is directed toward the substitute resource.

Figures 3 through 6 show that as the days of allowable fishing are reduced, the supply of surf clams decreases and the price per bushel increases. In the quahog market, the supply increased as did their price per bushel. These simulations represent the decrease in surf clam supply and increase in quahog demand explained above and illustrate the displacement of effort to the substitute resource. If the parameter for the limited access policy (parameter D) is chosen such that the two populations can sustain the resulting harvests, the future resource benefits are preserved. A limited access model, such as the one presented in this article, could therefore be employed to produce economically efficient and biologically sustainable resource usage.

PART FIVE: SENSITIVITY ANALYSIS

There remains debate over appropriate biological parameters for these two populations. In addition, the returns to time parameter, g, was estimated using the supply histories for the fishery. Simulations may be repeated using a range of estimates for these parameters to test the effect of the estimates on the simulations. Given the numerous parameters involved in this model, there are a significant number of possible different combinations of estimates. To maintain a clear picture and keep this article a reasonable length, one management regime is implemented for the simulations of model robustness (parameters for allowable fishable days remains constant at 250 days). The parameters returns to time (g), population growth rate of surf clams (s), and population growth rate of quahogs (y) are varied independently of each other.

Returns to Time

How does the estimation of the returns to time parameter, g, affect the harvest pattern? Changing this parameter did have an impact on the harvest pattern, for obvious reasons (values of g = 0.5, 0.86 and 0.9 were used). Quahog harvest is inversely related to the returns to time. In the case of the surf clam, greater returns to time results in higher harvests. This result emphasizes the importance of general equilibria discussion in the results section.

As the returns to time increase, the opportunity cost of fishing the quahog is effectively increased. Therefore more effort is directed to the surf clam fishery. The result is an increased supply and decreased price of surf clam (see Figures 11 and 12). The now lower price for the preferred surf clam reduces demand for the substitute quahog. As Figures 9 and 10 illustrate, there is a reduction in the harvest and price of the quahog.

While these simulations show that the estimate of returns to time affects the result, they highlight my previous conclusion. Consideration of general equilibria is essential to create effective regulation.

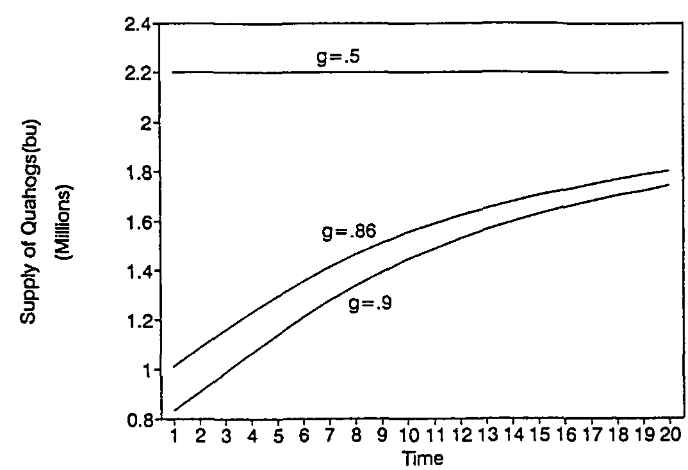

Figure 9. Sensitivity of supply of quahogs to parameter g.

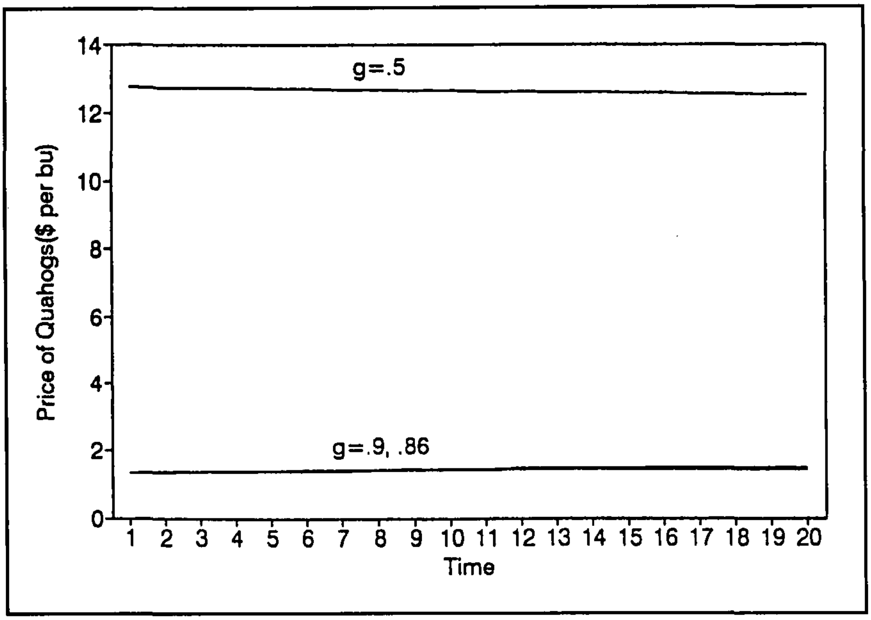

Figure 10. Sensitivity of price of quahog to parameter g.

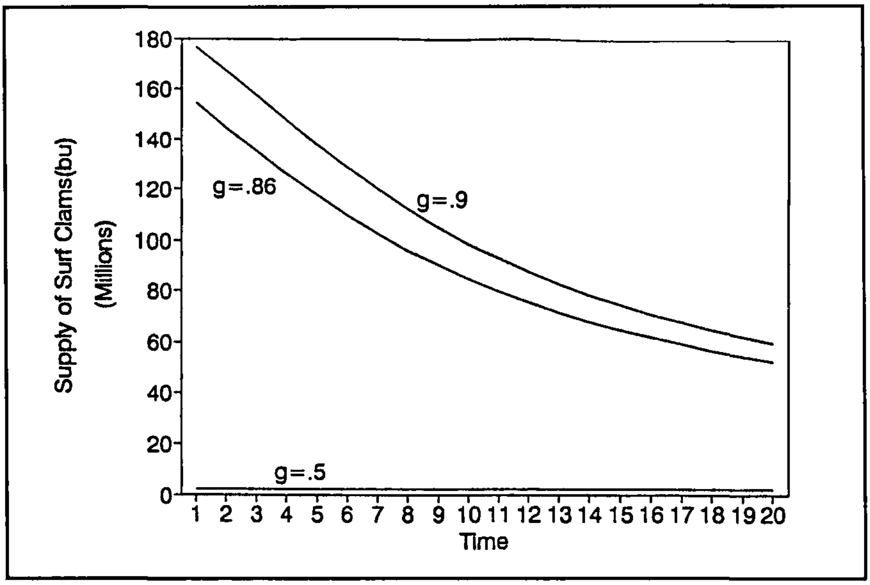

Figure 11. Sensitivity of supply of surf clams to parameter g.

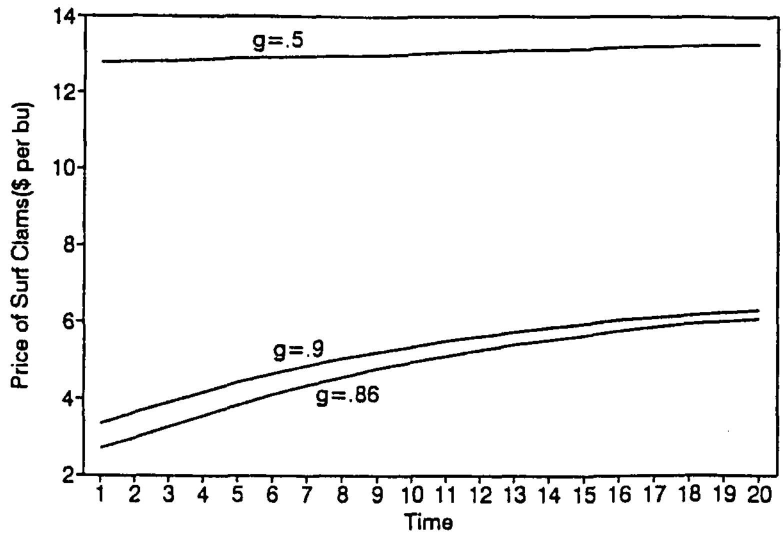

Figure 12. Sensitivity of price of surf clams to parameter g.

Surf Clam Population Growth Rate

To illustrate the effect the population growth rate of the surf clam exerts on the resulting harvest patterns, a series of simulations was run using different values for the parameter, s. The values of 0.0001, 0.00067 and 0.001 were used. Using a range of values was intended to address the controversy over the appropriate value for the species' growth rate. Interestingly, plotting the quahog and surf clam harvests for the different values of s, Figures 13 through 16, show that the harvest patterns are strikingly similar. On average, deviations do not appear until the 10th iteration. For the purposes of this model we can conclude that the parameter values for s do not significantly affect the conclusions made about the different policy regimes (changing the value of D).

Quahog Population Growth Rate

Although the value estimated for the population growth rate of the surf clam has no substantive effect, does the estimation of the population growth rate of the quahog? To answer this question we may again use different values for the parameter y, keeping all other parameters constant, and plot the resulting harvest patterns. Values of 0.00001, 0.0001 0.0002, and 0.0003 were used (see Figures 17-20).

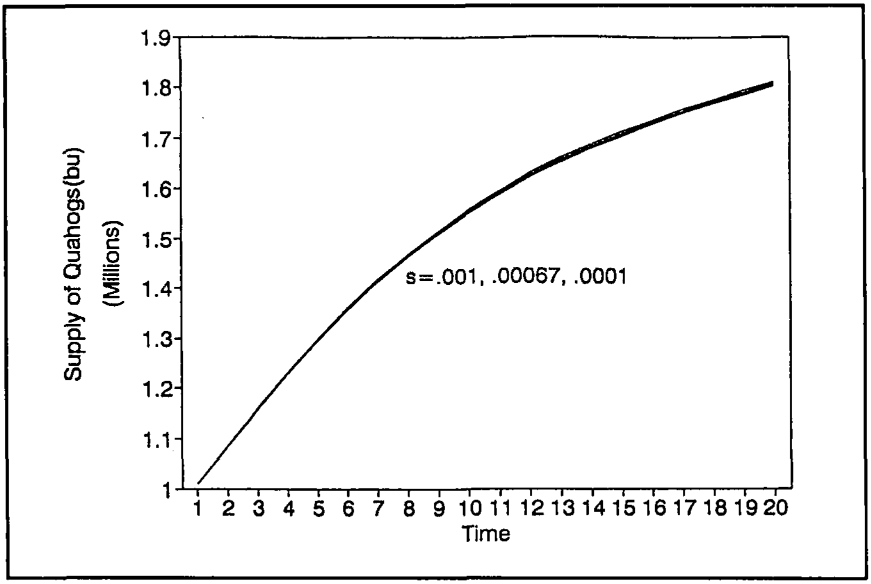

Figure 13. Sensitivity of supply of quahogs to parameter s.

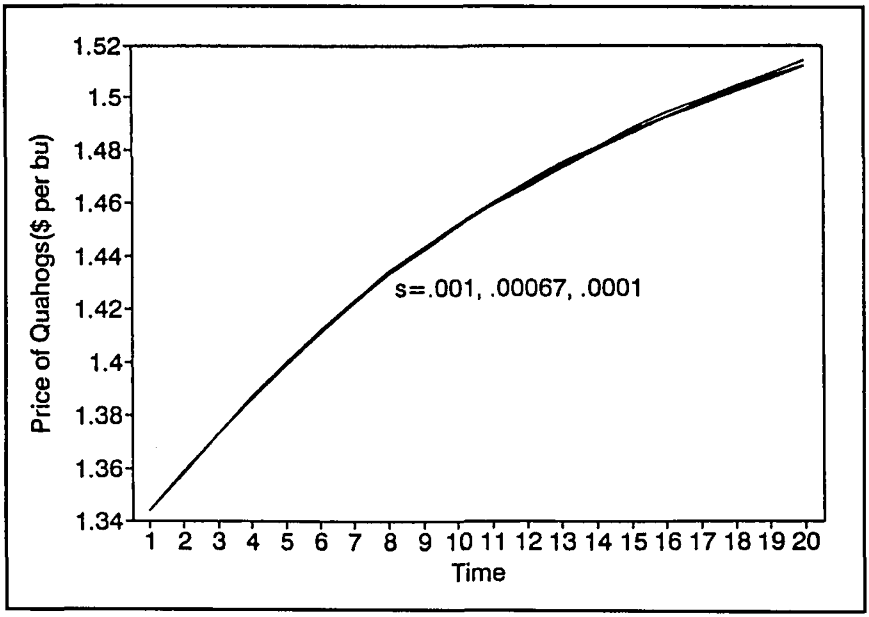

Figure 14. Sensitivity of price of quahogs to parameter s.

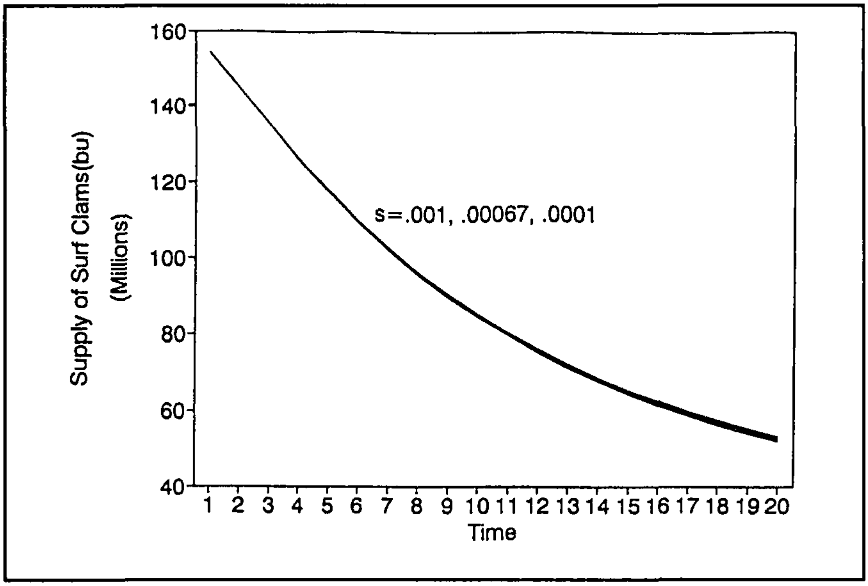

Figure 15. Sensitivity of supply of surf clams to parameter s.

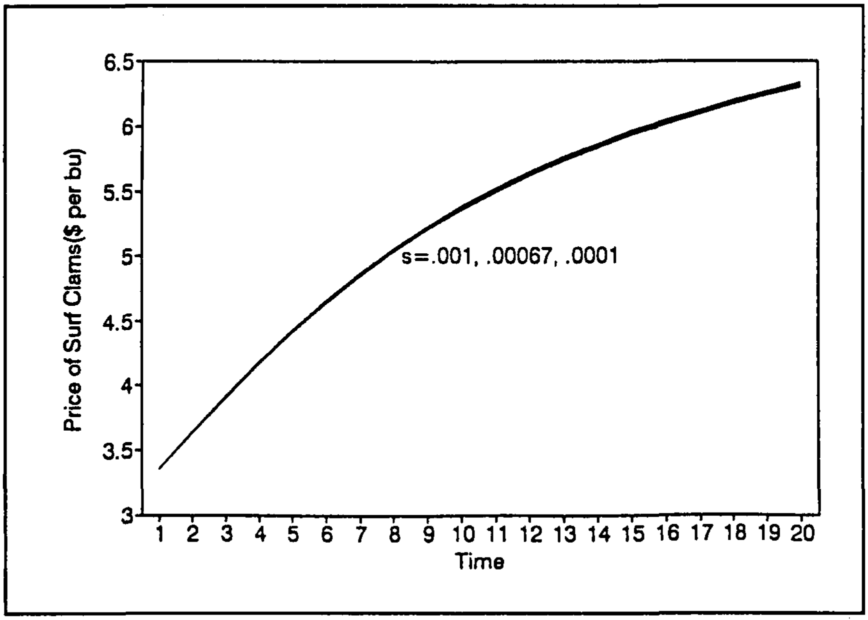

Figure 16. Sensitivity of price of surf clams to parameter s.

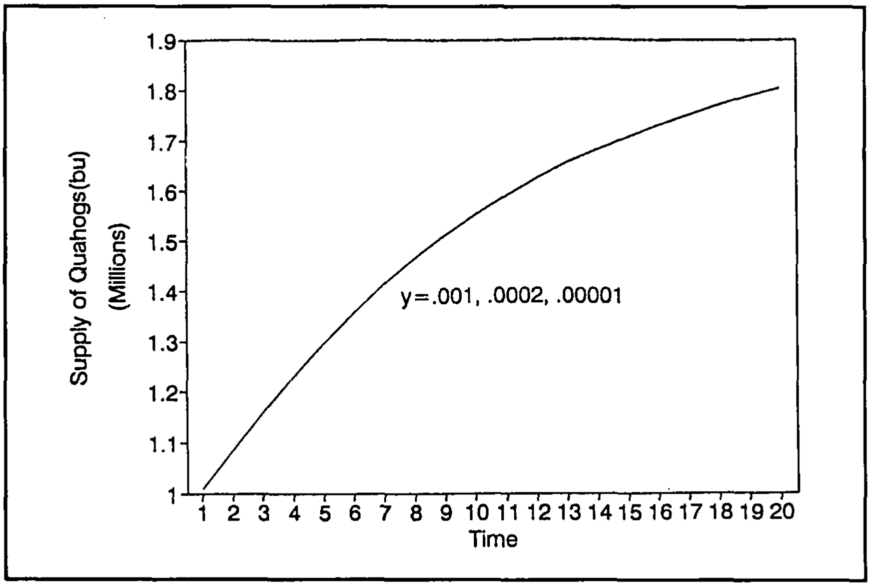

Figure 17. Sensitivity of supply of quahogs to parameter y.

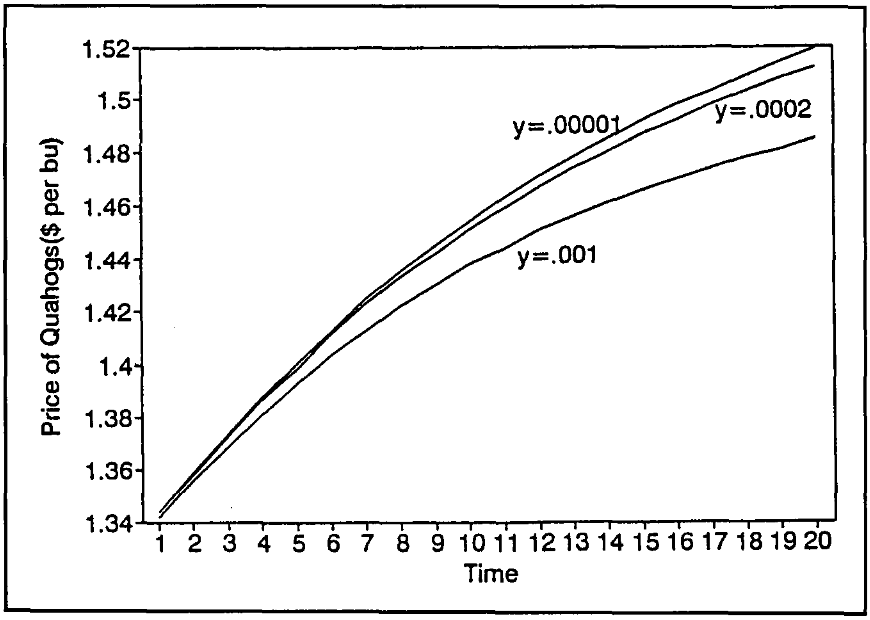

Figure 18. Sensitivity of price of quahogs to parameter y.

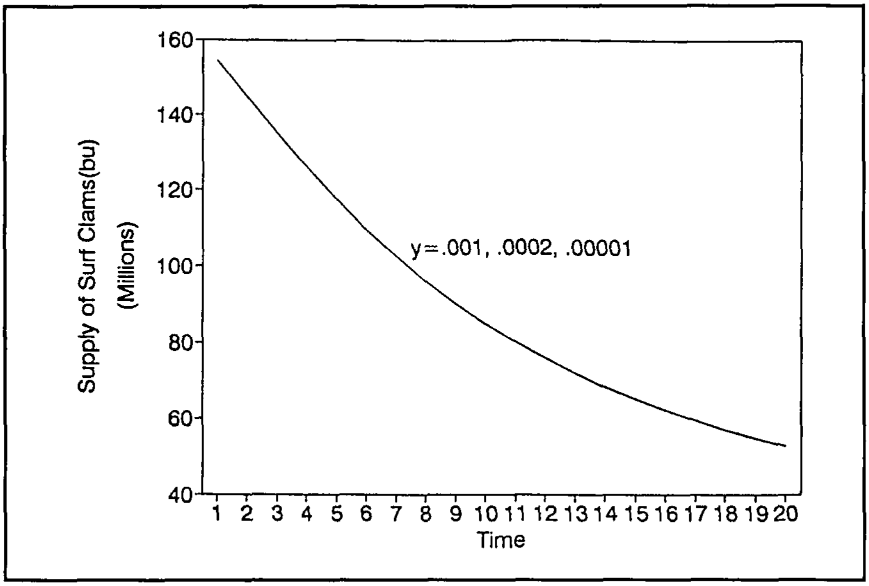

Figure 19. Sensitivity of supply of surf clams to parameter y.

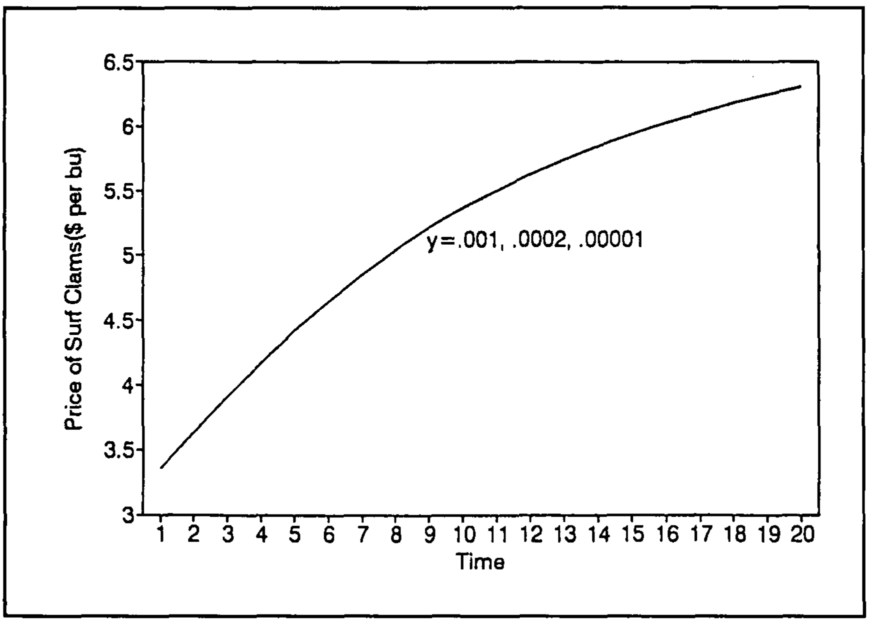

Figure 20. Sensitivity of price of surf clams to parameter y.

In these figures the harvest patterns are virtually indistinguishable from one another. In Figure 18 the quahog prices do vary according to the growth rate chosen. The largest difference, however, is only five cents. The conclusion is that while the estimation of the y parameter does affect the price simulations, the effects are minimal.

CONCLUSION

To study the efficacy of limited access management, this article focuses on the inter-relatedness of two natural resources: surf clams and quahogs. In an effort to reduce the overfishing in the surf clam fishery, a moratorium on new entry and a limited access program were implemented. This case was the first federal level attempt at limited entry in fisheries in the United States; therefore, it serves as an example for future policies. While management provided provisions for both fisheries, the limitations were never implemented in the quahog fishery. The result was the displacement of excess harvesting onto the delicate quahog population. Is there an inherent flaw in limited access policies? Should this regulatory technique be rejected for other substitutable resources?

To answer these questions I used a model which incorporates the economic and ecological factors as well as the joint-market for the two resources. By using one parameter for regulation, this model implements regulation of both species. Individual fishers must therefore decide which of the two species to harvest, and it avoids excess effort being re-directed to the unregulated fishery. This model therefore asks, how does limited access affect the relationship between primary and substitute resources?

Three main questions are answered by the simulations. In a limited access regime will excess effort be displaced to substitute resources? Will there always be an interior solution to the profit maximization problem? How sensitive are the models to changes in the parameters? The answers to these questions are used to evaluate the efficacy of limited access.

First, as shown in the simulation series, as access becomes more limited, effort is directed toward the substitute. This result may lead one to question, if time is restricted why would one spend valuable time fishing an inferior product? Figures 7 and 8 demonstrate the importance of considering general equilibria in regulatory policy and the dynamics that generate this seeming paradox.

The figures also show that within the time series simulated there is always an interior solution. It is more profitable to distribute effort between the two fisheries. Because effort will continue to be directed toward both species it is crucial that the management policies address the inter-relatedness of the resources.

Tests of sensitivity show that the model is robust with respect to changes in the parameters. Figures 9-20 illustrate the robustness of the simulations. The robustness of this model increases the reliability of its results.

Finally, is limited access an efficient policy? My conclusion is, it depends. The effects of limited access on prices, supplies, and population are a function of a complex ecological and economic system. Failure to address market incentives and general equilibria dooms resource management to displace effort to substitute resources; this fishery is one such example. Of great concern are resource systems where the substitute regenerates at a lower rate or has a smaller initial stock than the primary resource. Initially, focusing effort onto the substitute may increase supply; however, the long-run result may be a supply bust because the increased effort is unsustainable.

In the best case scenario, limited access policies integrate the associated general market equilibria and the biologically sustainable harvests of the substitute. Limited access policies which view resources as a system of economic and ecological factors may generate efficient usage of both primary and substitute resources. The simulations surf clam and quahog fisheries presented in this article demonstrate the absolute necessity to integrate the economic and ecological aspects of both primary and substitute for a successful limited access policy.

APPENDIX

Estimation of Price Functions

In an attempt to achieve better estimation of the price function, a system of simultaneous equations was estimated using three staged least squares. Quarterly data was available for the period of 1978:1 to 1986:1 [2]. The four estimated equations and the values are listed below. A superscript s denotes a supply equation, and a superscript d denotes a demand equation (see Table 4).

Cost of capital is measured by the producer price index for ship building and repairing, and cost of labor is estimated using quarterly wages in the shellfish industry from the Bureau of Labor Statistics, ES-202 program [8]. All values were deflated using the implicit GNP price deflator [9], and logs were taken of all series.

Table 4. Variables Used in Price Function

c	constant
Suffix of land	landings (the quantity harvested)
Qp	price per bushel of quahogs
SCp	price per bushel of surf clams
Cap	cost of capital
W	cost of labor
Qplant	number of plants processing quahogs
SCplant	number of plants processing surf clams

Equation One: Surf Clam Supply

The price of surf clams (SCp) and quahogs (Qp) and the cost of capital (Cap) and wages (W) are regressed on the supply of surf clams ($SCland^s$) (see Table 5).

$$SCland^s = c + \beta_0 Q_p + \beta_1 SCp + \beta_2 Cap + \beta_3 W$$

Equation Two: Surf Clam Demand

The price of surf clams (SCp) and quahogs (Qp) and the number of surf clam processing plants (SCplant) are regressed on the demand for surf clams ($SCland^d$) (see Table 6).

$$SCland^d = c + \beta_0 Qp + \beta_1 SCp + \beta_2 SCplant$$

Equation Three: Quahog Supply

The price of surf clams (SCp) and quahogs (Qp) and the cost of capital (Cap) and wages (W) are regressed on the supply of quahogs ($Qland^s$) (see Table 7).

$$Qland^s = c + \beta_0 Qp + \beta_1 SCp + \beta_2 Cap + \beta_3 W$$

Equation Four: Quahog Demand

The price of surf clams (SCp) and quahogs (Qp) and the number of quahog processing plants (Qplant) are regressed on the demand for quahogs (see Table 8).

$$Qland^d = c + \beta_0 Qp + \beta_1 SCp + \beta_2 Qplant$$

Table 5. Coefficients of Surf Clam Supply Equation

Coefficient	Estimate	SE	*T*-statistic
C	–908.217	2826.19	–0.321357
β_0	35.6740	114.667	0.31111
β_1	–7.73065	23.0757	–0.335012
β_2	195.469	600.295	0.325621
β_3	–0.58503	3.0204	–0.019346

Table 6. Coefficients of Surf Clam Demand Equation

Coefficient	Estimate	SE	*T*-statistic
c	13.8111	1.41551	9.75698
β_0	0.988806	3.01680	0.327766
β_1	–2.302214	2.06743	–1.11353
β_2	1.14920	0.75667	1.51875

Table 7. Coefficients of Quahog Supply Equation

Coefficient	Estimate	SE	T-statistic
c	801.746	2214.16	0.36210
β_0	−30.9466	89.8303	−0.344501
β_1	5.60136	18.0689	0.309999
β_2	−166.111	470.308	−0.353198
β_3	−2.76313	2.44511	−0.113006

Table 8. Coefficients of Quahog Demand Equation

Coefficient	Estimate	SE	T-statistic
c	15.0434	0.572166	26.2920
β_0	1.10388	2.01151	0.548781
β_1	-1.33033	1.21785	−1.09236
β_2	0.214462	0.142302	1.50708

To incorporate this additional information into the model, an explicit equation for price for each species needs to be estimated. For the surf clam it is:

$$\text{(a)}\quad \text{SCland} = \alpha_0 + \alpha_1\,\text{Qp} + \alpha_2\,\text{SCp}$$

Using that the elasticity (demand) of surf clam landings with respect to the price of surf clams is −2.302214 (β_1, Table 6), then α_2 can be solved for using the following:

$$\text{(b)}\quad \text{Esc} = \frac{\text{SCland}}{\text{SCp}} * \frac{\text{SCp}\wedge}{\text{SCland}\wedge}$$

where ^ denotes the mean value

In (a) α_2 equals the price elasticity, therefore (b) can be solved for α_2 which is, −185585.94. Next α_1 can be solved for using the samė process and the three staged least squared output for the cross-price elasticity which is 0.988806 (β_0, Table 6). The value for α_1 is 79712.132.

Now to solve for the constant α_0. The constant represents the harvest when the price of surf clams and quahogs are both zero. The inverse log of equation two is

$$\text{(c)}\quad e^{\text{Ln SCland}} = e^{(\text{C}+\beta 0 + \beta 1 + \beta 3\text{Ln SCplant})}$$

where $e^{\text{Ln SCland}} = \alpha_0$ in equation (1)

Solving (c) for α_0 ($e^{\text{Ln SCland}}$) yields 10516542.

The same procedure can be used to solve the following equation for the quahog.

$$\text{(d)} \quad \text{Qland} = \alpha_0 + \alpha_1 \text{Qp} + \alpha_2 \text{SCp}$$

Resulting in α_0 equals 105165.42, $\alpha 1$ equals –628.07246, and α_2 equals 269770.23. The price functions used in the simulations are therefore:

$$\text{(e)} \quad \text{SCp} = \frac{10516542 - \text{SCland}}{185585.94} + 0.429516\ \text{Qp}$$

$$\text{(f)} \quad \text{Qp} = \frac{105165.42 - \text{Qland}}{628.07246} + 429.52087\ \text{SCp}$$

Estimation of Parameters

Quahog Population Growth Rate

The parameters for the intrinsic population growth and the environmental carrying capacity, y and v, are biological aspects of the quahog species (these replace J, E in the general equation 8). The starting biomass of quahogs from Long Island to Virginia was estimated to be 5.4 billion lbs. This estimate was made by a 1976, NMFS shellfish assessment cruise using the area swept method, stratified by quahog density, depth range, and geofigureic region [10]. The value 5.4 billion pounds of meats was used for the estimate of the carrying capacity of the quahog.

The best estimate of the intrinsic population growth rate of the quahog is in dispute. Some fishery advocates claim that the growth rate is essentially zero, and the fishery should be managed as a depletable, non-renewable resource. The fact that the majority of the resource currently exploited is approximately one hundred years old does promote significant concern for its ability to recover from extensive fishing pressure. More alarming, however, is the fact that no new recruitment of quahogs has ever been detected by the fishery [2].

To assume that there is absolutely no population growth ignores the simple fact that somehow the population has grown to its present size. The extremely slow population growth, characteristic of long lived species, and lack of any observed successful sets indicates that the value for the population growth rate should be less than one percent. Therefore, a range of values for population growth, including zero, is used for the computer simulations. The different estimates of the growth rate can be used to test the sensitivity of the results to different estimates of this variable. For simulations in which the y parameter is constant the estimate 0.02 percent is used.

Surf Clam Population Growth Rate

A rough estimate for the surf clam stock in 1986, was 1.2 billion bushels [3]. The sum of the harvests since 1950, and the standing stock in 1986, is an overestimate of what the population would be in the absence of human intervention. To allow for population reduction through natural mortality the sum of the standing stock and one-half of the total bushels harvested provides a rough approximation of the environmental carrying capacity, parameter c, for this species [3].

$$1986 \text{ stock} + (0.5) \text{ total harvest } (1950\text{-}1985) = 1.9425 \text{ billion} \tag{14}$$

The probability of a good recruitment of surf clams is estimated to be 5 percent. A good recruitment is defined as a year class consisting of four billion recruits [6]. The mean weight of a year one clam is 0.004 lbs. Therefore a good year results in an increase in the population of sixteen million lbs, a 0.067 percent increase above the standing stock. The estimated value for the intrinsic growth rate of the surf clam population is 0.067 percent.

Returns to Capital and Labor

Estimates of the production parameters α and β were determined using cost shares [11]. This models assumes a Cobb-Douglas production function of the form $Q = A_z T_z K^\alpha L^\beta$ with constant returns to scale. Utilizing these assumptions:

$$\alpha = \frac{r*K}{(r*K) + (w*L)} \tag{15}$$

$$\beta + \frac{w*L}{(r*K) + (w*L)} \tag{16}$$

where K and L are optimal amounts of capital and labor, and r and w are their associated costs. When the sum of α and β exactly equals one, the optimal amounts of capital and labor are undefined. To avoid this problem (which results in a series of zeroes for the simulations) the estimates of these parameters were rounded down. Using estimates of the cost of capital from *Amendment Eight* [3] and the cost of labor from *Employment and Wages* [9], SIC 0913, α is approximately 0.8 and β is 0.1.

Returns to Time

The parameter g reflects the decreasing returns to time spent fishing. It incorporates the wear of time on the crew and the vessel. In addition it reflects the decrease in biomass (decrease in parameter A_i, $i = c, q$) which decreases catch per hour. Plotting the log of hours spent fishing versus the log of the catch and estimating this function provides an estimate of the return to time. Using this method I estimate the parameter value of g to be 0.82.

Abundance Parameter

In building the population dynamics model it is assumed that the populations of both species are significantly less than the environmental carrying capacity. It is for this reason that the beginning value for the abundance parameter is estimated to be 0.3. A result of the linearization of the growth function is that the population growth rate does not slow as the population approaches the carrying capacity. If the harvest rate is less than the growth rate then it is possible for the population to increase until the abundance parameter is greater than one. This did not occur in these simulations.

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