JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT 6, 287-296 (1979)

Exploitation of the Lobster Fishery: Some Empirical Results[1, 2]

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Received September 18, 1978; revised January 18, 1979

This paper analyzes the optimal and free market utilization of the lobster fishery and applies the results to two fishing areas in Canada. Biomass relationships and a production function are estimated and the empirical results are used to calculate hypothetical optimal fishing solutions. The welfare losses from overutilization of the fishing areas are examined.

In this paper biomass equations and a production function for two lobster areas in Canada are estimated. The equations are used to calculate fishing solutions when the fishery is optimally exploited and when utilization of the fishery is unregulated. The solutions are compared and social welfare losses are examined.

When utilization is unregulated, solutions are nonoptimal for two reasons. First, fisherman do not properly account for the effect of their fishing on future stocks of fish and thus they tend to nonoptimally deplete the stock of fish [3, 5]. Second when effort is applied to the fishery, fisherman receive not just the marginal product of their effort but they also appropriate the rents accruing to the resource. This extra return on effort in any time period tends to lead fishermen to enter the industry until the rents are dissipated and effort is paid the value of its average rather than marginal product. This type of overutilization of the fishery results in a social wastage of effort in any period [4, 6, 11].

This paper represents the only paper we know of in which the biomass equation and production function are separately estimated and combined to find equilibrium and optimal solutions (cf. [1] and [12]). Thus while the model is very simplistic the results are most suggestive and demonstrate the numerical magnitudes involved in fishing solutions and the way for further empirical work.

[1] Working Paper No. 78-30, Brown University.

[2] We are indebted to Gordon Douglas for help in estimating the biomass equation and compiling references. We are indebted to Herbert Mohring, Anthony Scott, and two anonymous referees for helpful comments on earlier versions of this paper.

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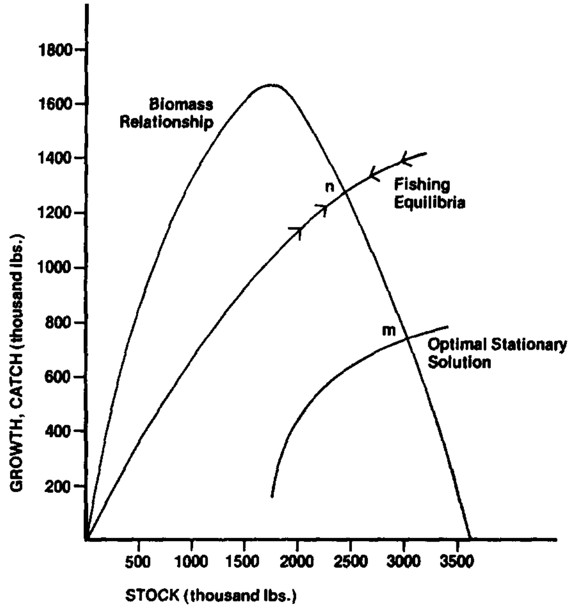

FIG. 1. The bioeconomic relationships.

1. THE MODEL

The Biomass Equation

The growth and number of lobsters in an area is dependent on their environment: temperature, food sources, and predators. A maximum naturally sustainable population exists determined by food availability and crowding which affects reproduction, cannibalism, and growth. Up to the maximum population level, population growth will occur at various rates. Taking an aggregative approach to this relationship which ignores the details of death, reproduction, and age structure, we postulate a local quadratic relationship between population and population growth measured in pounds of fish.[3]

$$dX/dt \equiv \dot{X} = aX - bX^2 \tag{1}$$

where X is population in time t and $\dot{X}$ is the gross change in area population. Maximum population is a/b. Maximum growth is $a/2b$.

If there is fishing, catch in time t, Q, reduces the population so that net growth is $\dot{X} - Q$. In a stationary fishing solution $\dot{X} = Q$, or catch exactly matches the gross growth in lobster stock in each period. A biomass equation is illustrated in Fig. 1, plotting growth in the stock against the stock.

[3] See Lotka [8] and Beverton and Holt [2] on this formulation. It would be desirable to incorporate water temperature into the analysis. Lobsters grow and mature much more quickly in warmer water. It takes about 80 molts (shell changes) for a lobster to reach sexual maturity at a weight of about 1 lb and a carapace length (body length excluding tail and claws) of around 3 in. This molting to maturity takes 8 years in Nova Scotia, 5 to 6 years in Massachusetts, and 2 years in controlled high-temperature laboratory conditions [7]. To incorporate temperature would require specifying some of lag structure to account for the effect of previous bottom temperatures on current population growth.

The Production Function

Lobster catch in an area is a function of the stock of lobsters and fishing effort as measured by the number of traps or man days. A variety of other factors such as water temperature and season length which are represented in this theoretical section by a parameter A affect catch. These effects are analyzed in the empirical sections below. The production function is

$$Q = AX^{\alpha}E^{\beta}, \tag{2}$$

where E is effort and A is a shift factor.

Theoretical Solutions

The optimal solution. The optimal solution for a fishing area is that which maximizes the present value of profits. Such a solution could be reached by assigning ownership of the fishery to one private entity or through government regulation. The present value of profits is

$$\int_0^\infty e^{-\delta t}(pQ - wE)dt, \tag{3}$$

where p is the price of catch, w the price of effort, and δ the discount rate. Maximization is constrained by the equation of motion for the system where net additions to the stock of fish are $\dot{X} - Q$, or $aX - bX^2 - Q$, and by the production relationship which we rewrite as $E = A^{-1/\beta}X^{-\alpha/\beta}Q^{1/\beta}$.

Thus the current value Hamiltonian for the maximization problem is

$$H = e^{-\delta t}[(pQ - wA^{-1/\beta}X^{-\alpha/\beta}Q^{1/\beta}) + \lambda(aX - bX^2 - Q)],$$

where λ is the costate variable. Necessary conditions for an optimum are that at any point in time

$$\frac{\partial H}{\partial Q} = (p - w\beta^{-1}A^{-1/\beta}X^{-\alpha/\beta}Q^{1/\beta-1}) - \lambda = 0,$$

$$\partial(e^{-\delta t}\lambda)/\partial t = -\partial H/\partial X = -e^{-\delta t}[-wA^{-1/\beta}X^{-\alpha/\beta-1}Q^{1/\beta}\alpha/\beta + \lambda(a - 2bX)].$$

Rearranging we get

$$w = (p - \lambda)\beta A^{1/\beta}X^{\alpha/\beta}Q^{1-\alpha/\beta} \equiv (p - \lambda)\beta Q/E, \tag{5}$$

$$\dot{\lambda} - \lambda(2bX + \delta - a) = -wA^{-1/\beta}X^{-\alpha/\beta-1}Q^{1/\beta}\alpha/\beta, \tag{6}$$

where $\dot{\lambda} = \partial\lambda/\partial t$.

Viewing X as a capital good, λ is the shadow price of stock. In Eq. (5), λ relates to the opportunity cost of additional catch reducing stock. Thus $p - \lambda$ is the shadow value of catch.

In a stationary fishing solution where $dX/dt = dQ/dt = 0$ by differentiating Eq. (5), we know $\dot{\lambda} = 0$. The stationary value of λ in Eq. (6) equals its value in Eq. (5), or

$$\lambda = (wA^{-1/\beta}X^{-\alpha/\beta-1}Q^{1/\beta}\alpha/\beta)\ (2bX + \delta - a)^{-1} = p - (wA^{-1/\beta}X^{-\alpha/\beta}Q^{\alpha/\beta-1}\beta^{-1}) \tag{7}$$

for X and Q equal to their stationary values. We can substitute the biomass constraint on stationary solutions, $Q = aX - bX^2$, into (7) to solve for X and Q. Such a solution is illustrated later.

Free entry. Without regulation, we assume effort is applied in fishing until the rent to the fishery is dissipated, or effort receives its average product. Then

$$w = pQ/E \equiv pA^{1/\beta}X^{\alpha/\beta}Q^{1-1/\beta}. \tag{8}$$

Rearranging, for any X, Q is given by

$$Q = (wp^{-1}A^{-1/\beta}X^{-\alpha/\beta})^{\beta/\beta-1}. \tag{9}$$

Equation (9) is illustrated of the graph of Q_{equil} in Fig. 1. The curve represents the equilibrium Q for any X. Thus a stationary equilibrium occurs at n where $Q = \dot{X}$. To the left of $n\dot{X} > Q$, so that X is increasing and we are always moving toward n. To the right of $n\dot{X} < Q$, so that X is decreasing and we are always moving toward n. Thus in a market situation, equilibrium stock and catch move monotonically toward their values at n.

2. EMPIRICAL ESTIMATES

The Biomass Equation

We estimate the biomass Eq. (1) by ordinary least squares for two lobster areas in the Maritimes accounting for 5–6% of Canada's total catch. Clearly the two areas must be treated separately since the environments in terms of area size, food availability, temperature, etc., will be different. To find values for stock, a certain number of lobsters in both areas were tagged each year before the fishing season and stock is estimated from the percentage of tagged lobsters in the catch. (Stock at the beginning of the lobster season is defined to be that year's catch in pounds multiplied by the ratio of total tagged lobsters to tagged lobsters caught.) For this to be a reasonable estimate of the stock we must assume that tagged and untagged lobsters are caught at the same rate.[4] The gross change in stock in a year is the catch plus the net change in stock (the estimated change in stock between two seasons calculated from taggings).

The data on stock and catch is only for lobsters larger than the minimum legal catch size (carapace length of 2½″ for Miminegash and 3 3/16″ for Port Maitland). Thus by estimating the biomass equation with our data, we are estimating the growth function for the existing stock of harvestable fish, assuming that current catches do not influence the number of recruits in the future. Apparently for certain species such as lobster, this is not an unreasonable assumption as long as annual catches do not fluctuate too much. This would suggest that the annual growth of stock is a constant (the influx of recruits) plus a growth function for the existing greater-than-legal-size stock. Our estimates of various forms of such a function were unsuccessful. Thus the simple quadratic function presented below with a constant term of zero should be viewed as the function that provides the best local fit of our data and that best describes the growth of the existing stock of harvestable fish within the ranges observed. These problems clearly limit the interpretation of optimal solutions presented later, as will be discussed.

[4] See Paloheimo [9] on using tagged lobsters to estimate stock.

The biomass equations are estimated to be:

Port Maitland (1954–1969)

$$\dot{X} = \underset{(6.30)}{1.80167}\, X - \underset{(4.70)}{0.00051}\, X^2 \qquad R^2 = 0.42 \qquad DW = 1.72$$

Miminegash (1957–1971)

$$\dot{X} = \underset{(4.40)}{1.27024}\, X - \underset{(1.69)}{0.00039}\, X^2 \qquad R^2 = 0.08 \qquad DW = 1.97$$

The t statistics are in parentheses, although due to measurement errors in X they may not be especially meaningful. The Port Maitland equation is graphed in Fig. 1. By our locally fit equation, maximum growth is 1766 thousand lb and the natural equilibrium stock is 3532 thousand lb. For Port Maitland, while the sample points are quite variable, they are all to the right of the maximum growth point, which makes our locally fit function more palatable for application in this region.

The Production Function

The production function is taken from Tugwell's [13] extensive investigation of the production function. The function was estimated from 22 observations from various fishing areas in Nova Scotia, covering the years 1953 to 1960. When estimates of stock are available, the only measure of effort is simply the number of traps fished. We have no information on men, boats, and equipment but must implicitly assume some fixed relationships between these and traps—i.e., a fixed rate of fishing of traps. In Tugwells' work when there is information on both traps and numbers of fishermen, the latter variable is almost always insignificant whereas traps is almost always significant. Thus our assumption may not be too restrictive. We include season length in our equation, because it varies considerably over the 22 observations. We include average bottom temperatures and temperatures lagged which also vary considerably over the 22 observations.[5] This is an important variable since lobsters move around much more, covering more territory, as temperature rises. The production function in estimated form is

$$\ln Q = -1.57 + \underset{(4.23)}{0.48} \ln E + \underset{(4.56)}{0.44} \ln X + \underset{(1.32)}{0.16} \ln D + \underset{(2.81)}{0.45} \ln T_t + \underset{(2.81)}{0.30} \ln T_{t-1} \qquad R^2 = 0.94$$

where Q is lobster landings in thousands of pounds, E is fishing effort in hundreds of traps, X is lobster stock in thousands of pounds, D is season length in days, and T_t, T_{t-1} are average seasonal bottom temperature in degrees Centigrade. The t statistics are in parentheses. Note there are strong diminishing returns to both labor and the biomass. The small effect of changing season length holding traps fished and stock fixed is due to two facts. Longer seasons are

[5] The inclusion of T_{t-1} is difficult to defend. However, it is the specification of the production function with the other variables present that is available. For any area T_{t-1} and T_t should be highly correlated.

associated with the winter months when the level of daily activity is quite low. Second in most situations even with short seasons, fishermen do not fully utilize the full season. They harvest most of the lobster crop in much less time than the maximum allowed.

There are several possible sources of statistical bias in this production function. The best known problem is that effort is chosen according to the productivity rule in Eq. (8), and, therefore, in the production function, the error term and the independent variable $E(t)$ are correlated. It can also be argued that since our stock data are estimated from catch the error term and $X(t)$ are correlated. However, this seems unlikely since stock is estimated from the *ratio* of tagged catch to total catch (see above) and hence does not depend on the absolute level of catch or variations in catch due to factors in the error term. Note that it is not possible to properly simultaneously estimate the biomass equations and production function since there is almost no overlap in observations.

In using the production function in our calculation below we insert the season length and average seasonal temperature for the two areas we are examining. The season lengths for Port Maitland and Miminegash are, respectively, 185 and 61 days and the average seasonal temperatures are, respectively, 6.34 and 8.87°C. Inserting these values in the production function we get a measure of the normal shift factor A in Eq. (2) for one two areas.[6] The production functions for the two areas become

Port Maitland

$$Q = 2.26\, E^{0.48}\, X^{0.44}$$

Miminegash

$$Q = 2.51\, E^{0.48}\, X^{0.44}.$$

Prices

To solve the model presented in Section 1, we need information on prices. We have excellent month-by-month data on landed price of lobsters. In the results presented below the difference between the Port Maitland and Miminegash average price occurs because the Port Maitland season is in the winter and spring when prices are high and the Miminegash season is in the summer and early fall when prices are low.[7]

Our problem is finding values for w, the opportunity cost of effort. One way to calculate the opportunity cost of effort is to assume the prevailing fishing situation is one of complete rent dissipation. Then effort is paid its average product and this equals opportunity cost. Therefore, the opportunity cost of effort is simply total revenue divided by the number of traps. We follow this simplistic procedure. However, survey data from 1961 in Rutherford *et al.* [10] allow us to check the empirical validity of this assumption.

In Rutherford *et al.*, for our lobster areas, expenses per fishing enterprise are recorded. First, we evaluate capital and equipment costs in annual, or

[6] To avoid introducing uncertainty into the production process we assume that *within* an area there is negligible variation in average seasonal *bottom* temperature. This assumption appears to be reasonable

[7] Our figures are from Rutherford *et al.* [10] and Canada, D.B.S., *Monthly Review of Canadian Fisheries Statistics*, Queen's Printer.

rental terms. Capital stock valued at current prices per enterprise for lobster plus other fishing activities is given. We calculate an annual implicit rental for all activities on boats and shore equipment, based on interest payments at 6% and depreciation at 17.5% for boats and engines and 7.5% for shore equipment (rates suggested in Rutherford *et al.* [10]). Part of this annual rental is charged to lobstering according to the fraction of time items are used in lobstering as opposed to other activities. Then an annual rental on gear used solely for lobstering is calculated given a depreciation rate of 15%.

We subtract these calculated capital rentals to be charged to lobster fishing from total revenue. The residual is the return to the operators or fishermen. If this residual equals the opportunity wage of fishermen in other activities, our assumption of complete rent dissipation where opportunity cost equals average product is justified. For Port Maitland this is certainly the case.

The residual return to lobster operators in Port Maitland is $35.32/week in 1961. Operators spend 35% of their annual time lobstering, 21% in other fishing, 19% in other employment, and 25% unemployed. The weekly return to lobstering is $35.32, to all fishing is $47.00, to other employment is $42.00, and to all annual activities is $38.55. Therefore, an opportunity cost of time of $35.32 seems reasonable. For Miminegash where 27% of one's time is spent lobstering and 45% is spent unemployed in 1961, the return to lobstering per week is $60.54 versus an annual average weekly income of $42.98. Our opportunity cost of effort, set at the average product of effort in lobstering, may be too high for Miminegash.

In the solutions below, the discount rate used is 0.06 because that is the figure used in calculating the opportunity cost of effort.

3. SOLUTIONS TO THE MODELS

Given our estimates of the biomass equations and production functions, we calculate stationary solutions for optimal and equilibrium solutions, based on prices prevailing in 1961. Although our solutions are for stationary situations, we believe the equilibrium solutions are comparable with the actual situations prevailing in the lobster areas in 1961. First, the assertion of rent dissipation as discussed in the above paragraphs seems reasonable. Second, given discussions with local officials of the Department of Fisheries in Canada, it appears that p/w was constant for the last part of the 1950s and for the first half decade of the 1960s. That is, given a fixed price ratio we should have been approaching a stationary equilibrium with free entry. Free entry solutions are obtained by solving Eqs. (1), (2), and (9) for Q, E, and X. As stated above, for Port Maitland, the equilibrium solution is at n in Fig. 1. Optimal stationary solutions for Q, X, and E are obtained by solving Eqs. (1), (2), and (7). A curve of optimal stationary X, Q combinations for Port Maitland is represented in Fig. 1.[8] Given the biomass, the actual solution on the curve is at m. (Note that unlike the free entry solution, this curve is, of course, not an approach path since it assumes $\dot{\lambda} = 0$.)

Our numerical solutions for 1961 are presented in Table I. There are two

[8] Note that stationary catch follows to zero as stationary X falls below 1750 thousand lb. Below 1750, profits are negative. This means that if the biomass equation shifted leftward such that X_{max} (where $X = 0$) fell below 1750, this fishing area would not be profitable to fish.

TABLE I

Results

	Port Maitland			Miminegash		
Biomass equation	$dX/dt + Q = 1.80167X - 0.00051X^2$			$dX/dt + Q = 1.27024X - 0.00039X^2$		
Production function	$Q(t) = 2.26\, E^{0.48}\, X^{0.44}$			$Q(t) = 2.51\, E^{0.48}\, X^{0.44}$		
Lobster price/thousand lb	\$485			\$370		
Opportunity cost/hundred traps	\$1,421			\$950		
	Optimal solution	Free entry	Actual average 1959–1963	Optimal solution	Free entry	Actual average 1959–1963
Lobster stock (thousand lb)	3,050	2,490	2,467	2,450	1,125	1,273
Lobster catch (thousand lb)	745	1,330	1,183	801	936	1,094
Effort (100s traps)	112	454		122	365	
Ratio: catch/stock	0.25	0.53	0.48	0.33	0.83	0.86
Shadow price of future stock (λ)	36	n.a.	n.a.	68	n.a.	n.a.
Optimal tax/thousand lb catch	270	n.a.	n.a.	225	n.a.	n.a.
Annual resource savings: value of trap savings less value of reduced catch	\$202,173	n.a.	n.a.	\$180,470	n.a.	n.a.

main features. First, the free entry solutions for both catches and stocks and the actual situations in the areas are similar, differing at the most by 12% and as little as 1%. Despite the inadequacy of the biomass equation in terms of low explained variance, errors in measurement, and being defined for greater than legal size lobsters and the bias inherent in estimating the production function, our model predicts very well.

The second feature is the extent to which the optimal solution dominates the free entry solution. Comparing the two stationary equilibria, although the free entry solution has higher catches (179 and 117% of the optimal solutions for Port Maitland and Miminegash, respectively), the associated effort is much greater (405 and 300% of the optimal solutions, respectively) because the equilibrium stocks are smaller. The resource savings from being at the optimal solution—the savings in traps less the value of the reduced catch—are very large. For Port Maitland it is \$202,173 per year. These savings are 62% of the total value of the optimal catch.

To sustain the optimal solution through government regulation, catch could be taxed. With free entry and no regulation, effort is employed so that $w = pQ/E$. We want effort employed so that in Eq. (5) $w = (p - \lambda)\, \beta Q/E$. Thus we want to redefine p through taxation so that $p - t = (p - \lambda)\beta$ where t is a unit tax price. Thus the stationary $t = p - \beta(p - \lambda)$, where the stationary value of λ is defined in Eq. (7). From Table I, for Port Maitland $\lambda =$ \$36/thousand lb and the unit tax is \$270/thousand lb. This is 56% of revenue.

In the early literature on fishing [6, 11] the biomass effects and the dynamics of this problem were ignored. It is interesting to note that in our situation if we also ignore these effects (by setting $\lambda = 0$ in the stationary solution) and only examine the problem of overutilization of effort applied to the unpriced resource in any period, our results are minimally affected. Setting the unit tax equal to $t = p(1 - \beta)$, we move to a solution for Port Maitland where $X = 3015$ thousand lb, $Q = 796$ thousand lb, and $E = 13{,}100$ traps: Profits in this situation are \$199,908, representing a loss of only 1% relative to the optimal solution where $\lambda > 0$.

Our final comment concerns the adjustment process. Our equations satisfy the assumptions in Brown [3]. Thus in moving from the free market to optimal solution, starting at the initial X, λ should decline continuously and X increase continuously to their stationary values. This would imply a declining schedule of unit taxes to the stationary tax. In applying Eqs. (1), (2), (5), and (6) to our empirical results to solve for the optimal approach path, unfortunately the assumption of continuous time and adjustment does not hold up because the changes in Q, X, and E from period to period are noninfinitesimal. (This also presents a problem in the production function because X varies over the fishing season given the pattern of $\dot{X}$ and Q over the season. Given $\dot{X}$ and Q are large, our specification of costs and production is not very sophisticated.) If we formulate a discrete adjustment process in our nonlinear model [5, chap. 7] (where $\dot{\lambda}_t \approx \lambda_t - \lambda_{t-1}$ and $\dot{X}_t \approx X_{t+1} - X_t$), we do converge to the stationary solution (but a cyclical adjustment path can be involved). As a practical mattet and ignoring distributive considerations, given the limitations of our specification and estimation, for Port Maitland, for example, we would suggest an immediate move to the stationary solution at m. This would involve, for $X_0 = 2490$ thousand lb, setting t_0 such that Q_0 was reduced from the free market 1330 to 770 thousand lb, yielding an $\dot{X}$ of 560 thousand lb so that $X_1 = X_{\text{opt}} = 3050$ thousand lb. This would require an initial tax of $t_0 = \$217$/thousand lb, followed by a tax in all succeeding periods of \$270/thousand lb.

The suggestion that a regulator should move the fishing solutions to their optimal levels as quickly as possible is based upon the assumption that current resources in fishing can be immediately shifted to other uses (equipment sold off at prevailing prices and fisherman reemployed at the same compensation). This assumption may not be met and a more sophisticated economic and political approach might suggest a more graduated phasing out of the excess resources committed to fishing.

4. CONCLUSIONS

Our calculations indicate that the welfare losses from nonregulation of the lobster fishery are about 20 and 30% of the value of the current or free market catch in the areas we studied. The calculation of optimal solutions based upon the fitted biomass equations concerns reductions in the rate of harvest of stocks of greater than legal size lobsters, assuming that the annual influx of recruits is unaffected by catch. More sophisticated data could indicate that a reduction in the rate of harvest would stimulate recruits and bring even greater benefits from regulation.

REFERENCES

1. F. W. Bell, Technological externalities and common property resources, *J. Polit. Econ.* (1972).
2. R. J. H. Beverton and S. V. Holt, On the Dynamics of Exploited Fish Populations, Fisheries Investigations, Vol. 29, Ser. 2, Ministry Agriculture, Fisheries, and Food, London (1957.
3. G. Brown, An optimal program for managing common property resources, *J. Polit. Econ.* **82**, 163–174 (1974).
4. S. Cheung, The structure of a contract and the theory of a non-exclusive resource, *J. Law Econ.* (1970).
5. C. W. Clark, "Mathematical Bioeconomics," Wiley, New York (1976).

6. H. S. Gordon, The economic theory of a common property resource: The fishery, *J. Polit. Econ.* **62**, 124–142 (1954).
7. J. T. Hughes, J. J. Sullivan, and R. Shleser, Enhancement of lobster growth, *Science* 177 (1972).
9. J. E. Paloheimo, Estimation of catchabilities and population sizes of lobsters, *J. Fish. Res. Bd. Canad.* (1963).
8. A. J. Lotka, "Elements of Mathematical Biology," Dover, New York (1956).
10. J. Rutherford, D. Wilder, and H. Frick, "An Economic Appraisal of the Canadian Lobster Fishery," Fisheries Research Board of Canada, Ottawa (1967).
11. A. Scott, The fishery: The objectives of sole ownership, *J. Polit. Econ.* **63**, 116–124 (1955).
12. M. Spence, Blue whales and applied control theory, Tech. Rpt. No. 108, Stanford Univesity, Inst. for Math. Stud. in Soc. Sc. (1973).
13. M. Tugwell, Common property resource management: The maritime lobster fishery, unpublished Ph.D. thesis, Queen's University, Canada (1974).