A Bioeconomic Analysis of the Northwestern Hawaiian Islands Lobster Fishery

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Abstract *Several surplus production-based bioeconomic models are applied to the Northwestern Hawaiian Islands (NWHI) commercial lobster fishery. The model which best explains the biological dynamics of the fishery is a modification of the Fox model developed by the authors. Economic costs are applied within a number of conceptual frameworks to develop the first integrated bioeconomic model of the fishery. In another development, the opportunity cost of labor based on crew share at the open access equilibrium level of fishing effort is used instead of proxy wage levels. Given the costs incurred, the fishery appears to be self-regulating in terms of long-term fishing effort for maximum sustainable yield.*

Keywords Biological production models, fisheries economics, fisheries management, spiny lobster, slipper lobster.

Introduction

The Northwestern Hawaiian Islands (NWHI) lobster fishery is relatively unusual amongst the world's lobster fisheries being a distant-water fishery landing predominantly a frozen tailed product. For the first twelve years of its utilization (1977–1988), laissez faire conditions predominated with a minimum of biological regulation. However in 1989, problems of over-capacity were not resolved through voluntary exit of marginal producers, and the growth of Hawaii's commercial longline fisheries posed the possibility of short-term entry by additional vessels. As a result, proposals were circulated to implement limited entry into the NWHI lobster fishery, and interest was raised in determining the optimal level of harvest.

The fishery has been actively regulated and monitored only since 1983, thus providing a very short time-series of data for modeling the biological population dynamics. Similarly, fishing vessel operations in the NWHI lobster fishery and in alternative fisheries have not been stable, with substantial switching between fisheries. As a result, some of the statistical grounds for modeling the fishery appear weak. On the other hand, interest in developing a more refined management system for this fishery is growing, suggesting that even a preliminary model of the fishery would be valuable as a benchmark for evaluating alternative management measures. The empirical results of these models are surprisingly robust.

Two questions this study addresses are: a) what is the appropriate biological model to use for bioeconomic purposes in this fishery, and b) given a relatively new fishery, what are the implications of the choice between models? Clearly the period of time in which the NWHI lobster fishery has been prosecuted precludes a full test of the alternative surplus production model we develop in this paper. We have attempted to do this in another context (Yoshimoto and Clarke, *in press*). On the other hand, fishery management is an immediate and on-going process. In lieu of an integrated bioeconomic modeling approach to the problem, fishery managers are left with a number of discrete pieces of information on the fishery management problem but with no overall perspective on the potential range of alternative solutions to that problem. We believe one advantage of surplus production bioeconomic models is the use of limited information to provide such guidance. Obviously the results need to be tempered by a flexible and adaptive approach to management actions.

This paper presents the first full bioeconomic model of the NWHI lobster fishery. After a brief historical summary of how the fishery developed, we begin with the derivation of biological and economic production functions. Four established surplus production models along with a new refinement to a previously accepted model are used in developing a bioeconomic analysis of the fishery. Biological parameters are estimated from a limited time series of annual fishery-wide catch and effort data, then combined with price and cost information to construct the bioeconomic models. The third part of the paper compares the models. The fourth and fifth parts summarize the results of the bioeconomic models and their implications for the NWHI lobster fishery. Finally, we present some thoughts on the use of alternative biological surplus production models on management strategy.

Background

Commercially viable concentrations of the spiny lobster *Panulirus marginatus* (henceforth referred to as spiny lobster) were discovered in the 1970s in the NWHI (Fig. 1), a group of islands, banks, and reefs extending 1,200 nautical miles northwest of the main Hawaiian Islands (Uchida and Tagami, 1984). Almost immediately, a commercial trapping fishery for live spiny lobster developed in Hawaii and grew rapidly to include 10 vessels, which in 1981 landed 350 metric tons (t) with an ex-vessel value of $2.7 million. By 1982, the Honolulu market was unable to absorb this relatively large volume of live lobster, ex-vessel prices dropped, and the fleet contracted. At that time, some vessels began processing spiny lobster at sea and landing frozen tails, allowing access to the worldwide market for frozen lobster tails. Thereafter, vessel operators began expanding their
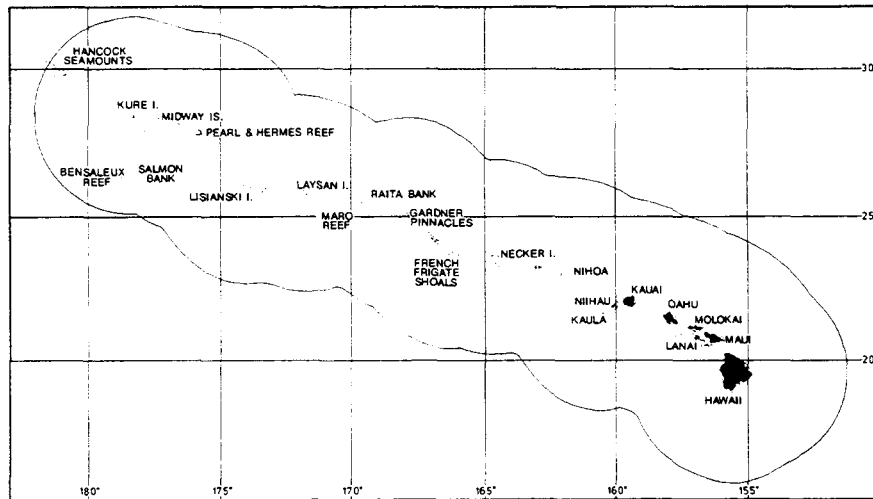
Figure 1. Hawaiian Islands with the Northwestern Hawaiian Islands demarcated by 161 degree west longitude.

efforts, and the fishery grew rapidly. Sixteen vessels participated in the NWHI lobster fishery in 1985, the same year vessel operators began targeting and landing significant quantities of the slipper lobster *Scyllarides squammosus*, which had been an incidental catch.

By 1986, the NWHI had the largest slipper lobster fishery in the United States, and its spiny lobster landings were second only to Florida's: combined landings had jumped to 1,000 t; ex-vessel revenue exceeded $6 million. Having developed into an industrial, multispecies lobster fishery, it was composed of medium- to large-sized fishing vessels (62–110 ft) traveling long distances and fishing for extended periods (Clarke and Pooley, 1988). However, entry and exit patterns showed considerable turnover in vessel participation in the fishery.

The NWHI lobster fishery originally operated under State of Hawaii regulations, but in March 1983, a federal fishery management plan (FMP) prepared by the Western Pacific Regional Fishery Management Council was implemented with the objective of protecting the reproductive spawning biomass. Initially, the FMP regulated only the spiny lobster fishery, but it was amended in 1987 to include slipper lobster. Regulations included minimum sizes, escape-vented traps, and returning berried females. Fishing effort was not restricted, except in a few areas declared off-limits as marine mammal and sea bird refugia.

From a purely biological perspective, the NWHI lobster fishery presented a unique situation in which fishery managers had relatively good estimates of the pre-exploitation condition of spiny lobster stocks based on the exploratory research surveys which preceded the commercial fishery. These initial surveys allowed for comprehensive biological assessments of the spiny lobster fishery as it developed (Uchida and Tagami, 1984; Polovina, 1989a). However, complications in monitoring the fishery quickly arose as the commercial fishery developed new gear configurations and as the importance of the slipper lobster landings grew. By 1986, effort levels appeared to be biologically excessive (Polovina *et al.*

1987), and several economic studies were initiated by the Honolulu Laboratory and the Council to examine management implications. But as fishing intensity stabilized, interest waned in managing the fishery through economic regulation until an apparent recruitment (or catchability) crisis late in 1989. The Crustacean FMP was amended in 1991 to limit entry into the fishery based on current levels of participation, and a flexible fishing season based on an annual quota was proposed for 1992. Economic optimization of the fishery has not really been considered; the limited entry and seasonal regulations are pragmatic and oriented toward preserving a threshold spawning biomass in the fishery (Polovina, 1991).

Methods

Production Models

Five models with distinctly different biological production relationships are assessed for their applicability to the NWHI lobster fishery: the Schaefer (1957) model, the Fox (1970) model, the Schnute (1977) modification of the Schaefer model, a threshold-type model as presented by Sathiendrakumar and Tisdell (1987), and our modified version of the Fox model. Hereafter, for the sake of brevity the models will be referred to as the Schaefer, Fox, Schnute, Threshold, and CY&P, respectively. They consist of three distinctly different production (*i.e.*, yield and effort) relationships: The Schaefer and Schnute models have a parabolic or logistic relationship, the Fox and CY&P models follow a Gompertz curve (Richards, 1959), and the Threshold model has a logarithmic curve that asymptotically approaches a maximum.

The Schaefer, Fox, Schnute, and CY&P models relate stock size, fishing effort, and yield to one another. Stock size adjusts to different levels of effort, and sustainable yield is a result of applied effort. As will be shown later, the yield-effort relationships can be quite different in terms of predicted results. The Fox model has had reasonable results when used for other lobster fisheries (Campbell and Hall, 1987; P. Breen, personal communication 1989). To our knowledge, the Threshold model has not previously been used for a lobster fishery. The Schnute model was applied by Polovina (1989b) to a system of simultaneous production relationships for forecasting in the NWHI lobster fishery. He estimated individual bank parameters using area-by-area catch and effort data and pooling the area results for a fishery-wide model.

The five models in our study are fit from the same NWHI logbook data used by Polovina (1989b), but catch and effort are pooled for the entire NWHI fishery.[1] We feel this more closely approximates economic considerations in the fishery. Vessel operators frequently fish various banks during a trip, and the decision to make a trip is not based on the average annual or seasonal productivity of any individual bank.

The generalized stock production model (Pella and Tomlinson, 1969) is

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[1] Whether bank-by-bank or fishery-wide analysis is appropriate biologically is a matter of concern. Some aspects of recruitment are clearly fishery-wide (*e.g.*, the circulation of lobster phyllosomes throughout the archipelago) while others are bank-specific (*e.g.*, settling out of larvae). Polovina (1991) found the CY&P model applied to fishery-wide data was consistent with bank-by-bank analysis.

$$dX/dt = rX - (r/K)X^m - C; \tag{1}$$

where dX/dt is the growth rate of biomass; r, the intrinsic growth; C, the catch rate; X, the current biomass; and K, the maximum stock level or virgin biomass. When $m = 2$, then

$$dX/dt = rX(1 - X/K) - C, \tag{2}$$

and the growth rate is of the logistic form. When $m \to 1$, then

$$dX/dt = rX \ln(K/X) - C, \tag{3}$$

and the growth rate follows a Gompertz curve (cf. Richards, 1959). The basic difference between the logistic and Gompertz curves is that the logistic is symmetrical while the Gompertz is not, implying, in an extreme case, the potential extinction of the fishery. Using the assumption of $C = qEX$, where E is the rate of fishing effort, q is the catchability coefficient, and catch per unit effort (CPUE) is defined by $U = C/E$, current biomass is given by $X = U/q$. The resulting biomass equation can then be used to convert Equations 2 and 3 into forms directly applicable to annual catch and effort data. With the Pella and Tomlinson (1969) method, an iterative procedure was tested to determine which value of m best fits Equation 1. However, the true value of m could not be estimated from the data on the NWHI lobster fishery because several quite different m values produce equivalently good fits. The R statistic, a measure of improved fit compared to reliance on the mean catch as the parameter value, is >0.98 for m values covering the range of those used in these production models: 2.0 (Schaefer), 1.01 (Fox), and 0.01 (Threshold). The fact that the true value of m could not be estimated with the Pella and Tomlinson model is probably due to the relatively short time series of data available (P. Tomlinson, personal communication 1990).

Two models use the finite difference approximation $dU/dt \approx (\overline{U}_{n+1} - \overline{U}_{n-1})/2$, where $\overline{U}_n$ is the average CPUE for a given year, n ($\overline{}$ denotes the mean):

Schaefer: $\quad (\overline{U}_{n+1} - \overline{U}_{n-1})/(2\overline{U}_n) = r - (r/(qK))(\overline{U}_n) - q(\overline{E}_n), \tag{4}$

Fox: $\quad (\overline{U}_{n+1} - \overline{U}_{n-1})/(2\overline{U}_n) = r \ln(qK) - r \ln(\overline{U}_n) - q\overline{E}_n, \tag{5}$

where $\overline{E}_n$ is the total effort expended in year n. The parameters r, q, and K are estimated by ordinary least squares (OLS) with a time series of catch and effort data.[2]

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[2] It would be useful to compare our estimates of K with pre-exploitation or fishery-independent measures of biomass. Unfortunately, comparable estimates of pre-exploitation biomass are not readily available because the gear used in early research cruises failed to sample slipper lobster. Polovina and Tagami (1979) estimated spiny lobster populations for a subsection of one of the banks (Necker Island) using depletion methods. Uchida and Tagami (1984) extrapolate those results and report a NWHI wide spiny lobster MSY range of between 210,000 and 435,000 lobsters above 8.25 centimeter carapace

Many bioeconomic studies incorporate biological parameters that have been estimated by the Schaefer and Fox models. Although some authors (*e.g.*, Uhler, 1980) suggest that finite difference models may be useful for economic analysis, others (*e.g.*, Schnute, 1977) have shown these models to be invalid for non-equilibrium conditions and have suggested that modified versions be applied to better represent the dynamic nature of fishery yield and effort interactions. Schnute (1977) argues that a major problem with the Schaefer and Fox models is that they can predict next year's CPUE without specifying next year's anticipated effort, contradicting almost all theory on fisheries biology. Another problem involves the finite difference approximation, which assumes that CPUE is linear over the course of a given year. Based on a review on monthly CPUE data from the NWHI lobster fishery (Clarke *et al.* 1987), this assumption is questionable. Thus, the Schaefer and Fox models are presented for comparison purposes only, while the Schnute, Threshold, and CY&P models are explored in greater detail in our paper.

Schnute (1977:594) developed a modified version of the Schaefer model using an integration procedure:

$$\text{Schnute: } \ln(\overline{U}_{n+1}/\overline{U}_n) = r - (r/(qK)) (\overline{U}_n + \overline{U}_{n+1})/2$$
$$- q(\overline{E}_n + \overline{E}_{n+1})/2. \tag{6}$$

For the CY&P model, we follow Schnute's lead and apply a similar approach to the Fox model, using a Taylor approximation (derivation in Appendix A):

$$\text{CY\&P: } \ln(\overline{U}_{n+1}) = (2r/(2 + r))\ln(qK) + ((2 - r)/(2 + r))\ln(\overline{U}_n)$$
$$- (q/(2 + r))(\overline{E}_n + \overline{E}_{n+1}). \tag{7}$$

By using OLS, the three constants can be estimated from Equation 7 by

$$\ln(\overline{U}_{n+1}) = c1 + c2 \ln(\overline{U}_n) + c3(\overline{E}_n + \overline{E}_{n+1}); \tag{8}$$

where $r = 2(1 - c2)/(1 + c2)$, $q = -c3(2 + r)$, and $K = e^{c1(2+r)/(2r)}/q$. The CY&P model incorporates the same nonlinear assumptions as in the Schnute model, and, as will be demonstrated, has a good fit to the NWHI commercial lobster fishery's limited time series data.

The Threshold model presents an interesting twist in the conventional yield-effort relationship. Unlike the previous models for which stock size varies with effort, the Threshold model shows decreasing returns to effort after reaching a critical level. This can be interpreted either as the result of competition among vessels or long-term population adjustments (Sathiendrakumar and Tisdell, 1987).

The Threshold model shows catch reaching its maximum asymptotically, expressed as $C = A - Be^{-kE}$, where C is catch and E is effort. The parameters A, B, and k can be estimated with the transformation

length. However the minimum size limit actually implemented was smaller: since the inception of Federal management a legal-sized spiny lobster equates to approximately 7.7 centimeters carapace length while the legal slipper lobster size equates to an 8.3 centimeter carapace (actual regulation is now by tail width).

$$\ln(A - \overline{C}_n) = \ln(B) - k\overline{E}_n; \tag{9}$$

where $\overline{C}_n$ is the total catch, $\overline{E}_n$ is the total effort for year n, and A corresponds to the maximum catch or threshold level of catch.[3] Although not specified by the original authors, we interpret k as the catchability coefficient and B as virgin biomass. With a method similar to that employed by Sathiendrakumar and Tisdell (1987), a value for A is chosen that is slightly higher than the highest combined catch levels recorded for each species of lobster. The initial value of A is then changed iteratively until the regression of $\ln(A - C)$ against E gives the best fit in terms of maximizing R^2. The Threshold model has been used for tunas that are exploited over only a portion of their range, but it seems applicable to a benthic fishery as well. It can be applied to lobster stocks in the NWHI because not all of the lobster population is subject to exploitation throughout the year. At certain times of the year, lobster are less vulnerable to trapping because of environmental effects (*e.g.*, sea state, water temperature) on behavioral activity, such as nightly foraging (Karnofsky and Price, 1989). Finally, minimum size regulations and escape vents limit the fishable proportion of the total population.

Catch and Effort Data

The basic unit of fishing effort in the NWHI lobster fishery is the trap-haul, and all vessels currently participating in the fishery use black, plastic traps made by one manufacturer. Bait and general fishing methods are also homogeneous throughout the fleet, and although differences between vessels do exist, all trap-hauls are assumed to be equally efficient for this analysis.

Catch and effort data for 1982–1989 are presented in Table 1. Length-frequency information taken from research sampling has been used to adjust 1982–1987 slipper lobster categories to account for the implementation of management regulations in 1988.[4] Catch per trap-haul for the two species has been combined into one unit stock because the targeting practices of fishermen are not known and the habitat of the two types of lobster overlap.[5]

Price

The revenue function is created by applying Hawaii's 1986–1988 average ex-vessel lobster price, adjusted for inflation, to the biological production functions.

[3] At low levels of effort (E), the Threshold model can predict negative catch levels (C). This is not a problem at reasonable effort levels. In an alternative specification, where A = B, the Threshold model is non-linear.

[4] Spiny lobster, the initial target species of the fishery, are reported in catch and effort logs as either legal, sublegal, or berried (egg-bearing females). These categories are also used for slipper lobster catches, which the fishermen voluntarily reported prior to their management in 1988.

[5] The post-settlement growth rates of the two lobsters are similar reaching minimum legal size at 3.1 and 3.3 years, respectively, for the spiny and slipper lobster (Polovina and Moffitt, 1989). The habitat for the two species generally overlaps in that spiny lobster are normally concentrated in waters 15–25 fathoms while slipper lobster concentrate at slightly deeper depths of 20–30 fathoms. Nonetheless the two species show no definite delineation by depth, and it is not possible to segregate effort by species from the catch and effort reports submitted by fishermen. The problem of modeling these two species with one production model has been raised repeatedly in the past two years, but no solution has been found.

Table 1

Number of Lobster Retained, Fishing Effort (Number of Trap-Hauls), and
Average Catch Per Unit Effort (CPUE) in the Northwestern Hawaiian Islands
Lobster Fishery, 1982–1989

| Year | Retained Lobster | | | Effort (in Trap-Hauls) | CPUE |
	Spiny Lobster	Slipper Lobster	Combined Total Lobster		
1982[a]	—	—	148,214	47,738	3.10
1983[b]	210,100	24,600	234,700	84,870	2.77
1984	667,300	205,100	872,400	363,024	2.40
1985	956,000	856,700	1,812,700	983,062	1.84
1986	896,400	891,000	1,787,400	1,352,580	1.32
1987	394,600	343,200	737,800	804,723	0.92
1988	889,000	168,600	1,057,600	845,200	1.25
1989	944,100	216,200	1,160,300	1,071,538	1.08

Note: The 1983–1986 data are from Clarke et al. (1987); 1987–1989 data are from Landgraf et al. (1990).

[a] The 1982 catch is estimated from weight of lobster landed; effort is estimated by back-extrapolating using 1983 levels of reported trapping intensity (where 1982 trap-hauls per trip are 75% of the number of trap-hauls per trip in 1983) and multiplying by the number of trips ($n = 19$) reported for that year.

[b] The 1983 data are extrapolated from 9 months of actual data to account for the entire year.

Real ex-vessel prices (in U.S. dollars) for Hawaii's spiny and slipper lobsters, calculated on a whole weight basis from nominal revenue data, adjusted for inflation to 1989 price index levels, are shown in Table 2 for 1982–1989 (Landgraf *et al.* 1990). The real (1988 base year) weighted average price of combined spiny and slipper lobsters was $4.55 per lobster for 1986–1988, the period for which detailed cost and effort data were available.

During the last 5 years, 95% of the lobster landed (by weight) from the NWHI have been frozen tails (Landgraf *et al.* 1990). Although some of them are sold locally to Hawaii's seafood wholesalers, most are transshipped to the U.S. main-

Table 2A

Average Nominal and Real[a] Ex-Vessel Price[b] per Pound (Round Weight) of
Combined Spiny and Slipper Lobster, Pounds Landed, and Nominal and Real
Total Revenue[b] in the Northwestern Hawaiian Islands Lobster
Fishery, 1982–1989

| Year | Price per Pound | | Round Weight | Revenue | |
	Nominal	Real		Nominal	Real
1982	3.60	4.78	187,000	673,000	893,401
1983	2.91	3.76	203,000	591,000	762,366
1984	2.58	3.22	1,017,000	2,624,000	3,279,079
1985	2.49	2.94	2,368,000	5,887,000	6,951,504
1986	2.72	3.14	2,202,000	5,982,000	6,907,832
1987	4.12	4.52	969,000	3,988,000	4,383,351
1988	3.56	3.69	1,405,000	5,000,000	5,187,290
1989	4.28	4.28	1,470,000	6,291,000	6,291,000

[a] Adjusted for inflation to 1989 Honolulu consumer price index levels.
[b] In U.S. dollars.

Table 2B
Average Nominal and Real[a] Ex-Vessel Price[b] and Number of Combined Spiny and Slipper Lobsters Landed in the Northwestern Hawaiian Islands Lobster Fishery, 1982–1989

Year	Price per Lobster		Number
	Nominal	Real	
1982	4.54	6.03	148,214
1983	2.52	3.25	234,700
1984	3.01	3.76	872,400
1985	3.25	3.83	1,812,700
1986	3.35	3.86	1,787,400
1987	5.41	5.94	737,800
1988	4.73	4.90	1,057,600
1989	5.42	5.42	1,160,253

[a] Adjusted for inflation to 1989 Honolulu consumer price index levels.
[b] In U.S. dollars per lobster.

land and compete with other worldwide sources of lobster for the U.S. market share. Landings of NWHI spiny and slipper lobsters account for <1% of the worldwide lobster production and only 20% of U.S. production (Samples and Gates, 1987). Therefore, NWHI fishermen are considered price takers in the international lobster market, and supply interaction with demand is excluded from our analysis.

Cost of Effort

Determining the economic cost of fishing effort can be a difficult process because bioeconomic models are constructed to indicate the optimum social investment in a fishery over the long run, while firm costs usually are viewed as short-run phenomena. Our paper follows the usual microeconomic and bioeconomic assumptions of a competitive market economy in which factor markets are in equilibrium and maximization of profits (net revenue) is the firm's decision criterion. Costs should reflect social opportunity costs (following Anderson, 1982). Pragmatically, where there is information on average private costs (as is the case for the NWHI lobster fishery), private costs closely approximate the social costs (Anderson, 1982):

$$TC \approx c * E;$$

where TC is the total cost (per trap-haul); c, average cost (per trap-haul); and E, effort (in trap-hauls). Cost per trap-haul should be chosen at the point which approximates the minimum point on the long-run average cost curve, *i.e.*, the point of long-run industry equilibrium (ignoring biological effects). This can then be assumed to be constant, which does not significantly affect the results (Anderson, 1982).

The cost of effort for the bioeconomic model can be estimated in two ways: average fleet costs, which combine the costs from the three vessel classes com-

prising the fleet, or "optimal" costs, which are derived from the vessel class (*i.e.*, Class II) that appears to be best suited for this fishery (Clarke and Pooley, 1988).[6] The unweighted average fleet cost per trap-haul was $4.60 over the 3 years for which detailed cost and operating information was available (1986–1988), compared with $3.48 for the Class II vessels (the vessel class with the lowest cost per trap-haul). We consider the latter to be the basic social opportunity cost of fishing effort. However, this cost should be adjusted for imperfections in the labor market in order to represent the long-run opportunity cost of lobster fishing.

The NWHI lobster fishery is a small component of Hawaii's economy and can be viewed as a price taker for most inputs. Within any individual fishing trip, extending fishing effort may increase marginal costs, but entry and exit patterns of this fishery and variation in trip duration indicate that the flexibility of productive inputs is sufficient to view operating and vessel costs per unit effort as constant. Furthermore, since lobster boats represent mobile capital capable of shifting between different fisheries (*e.g.*, Hawaii's longline fishery or the Pacific Northwest's crab fisheries), the opportunity cost of capital is reflected by the annualized market value of the vessels.

Only for labor does Hawaii's input market seem distorted for NWHI lobster fishing vessels. Labor payments in commercial fishing are outside normal employment practices, and conditions on the NWHI lobster fishing vessels are outside the norm of other fishing fleets in Hawaii. As a result, a number of NWHI lobster fishing vessel captains have had to hire crews from the Pacific Northwest and pay for their transportation to and from Hawaii. This poses a substantial problem for calculating the opportunity cost of labor since there is no truly comparable competitive labor market. Commercial fishing crews give up a certain income and take on a particular way of life in hopes of receiving a portion of the economic rents from the fishery and the profits of individually efficient producers. (In 1986, crew members on larger lobster boats received $148 per fishing day, while crew shares on the midsized boats ranged from $126 for efficient producers to $79 for inefficient producers.) The opportunity cost of labor for commercial fisheries has been calculated a number of different ways (Anderson, 1977; Clark, 1985). Clarke and Pooley (1988) argued that it is inappropriate to use manufacturing wage rates as proxies for the opportunity cost of labor on lobster boats because there is no occupational equivalent to distant-water commercial fishing. Instead, labor cost should be determined from the crew share at a point where the fleet appears to be in open access equilibrium (OAE), *i.e.*, where there are no rents. This can be viewed as the value of the marginal product of labor in which no resource rents are accruing to the crew (or the vessel).

Cost-earnings data indicated the fleet was breaking even in 1986, with an

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[6] A cost-earnings study (Clarke and Pooley, 1988) on the economic performance on the NWHI lobster fleet for 1986 revealed varying rates of return on lobster operations. Vessels were classified according to their physical and operational characteristics, and while certain sectors of the fleet showed a positive return on investment, overall the fleet returned $−198,000 on $6.214 million total revenue in 1986.

The vessel cost portion of the study included estimates on fixed and variable costs for all of the classes. Fixed costs included estimated capital costs (10% of investment) and annual repair, vessel insurance, administrative, and loan (interest payment) costs. Operating costs included all trip costs and crews and captains' shares. Vessel depreciation was fixed at 4% but included a supplemental component if annual vessel repair was less than 10% of depreciation.

average labor cost of $137.00 per crew member per fishing day (Clarke and Pooley, 1988). This labor cost represents a wage rate of approximately $10.00 per hour for 16-hour fishing days, substantially less than Hawaii's contract construction rate of $17.42 per hour in 1986 but about the same as the manufacturing wage rate of $8.86 per hour. Recalculating vessel operating costs (Table 3) with this labor cost provides the cost figure used in the remainder of our study: $2.97 per trap-haul, the minimum long-run average cost during a period of intensive fishing.

Bioeconomic Models

At a static equilibrium, dX/dt equals zero, and equations relating catch and effort can be obtained for the Schaefer and Schnute models

$$C = qKE(1 - qE/r), \tag{10}$$

and for the Fox and CY&P models

$$C = qKEe^{-qE/r}. \tag{11}$$

Once the yield-effort equations are established for the various models, reference points important for evaluating anticipated or predicted fishing effort can be determined by incorporating cost and revenue data. The economic portion of the bioeconomic models, as proposed by Gordon (1954), assumes constant price (p) for lobster and cost (c) for each unit of effort (or trap-haul), where revenue equals pC and total cost equals cE. The relationship between cost and revenue implies, that at OAE, biomass $\overline{X}$ is $c/(pq)$ (Clark, 1985).

Static OAE or maximum economic yield (MEY) disregards the difference between present and future values of funds. The idea behind MEY is that the fishery is managed as a capital good maximizing net present value (Clark, 1985). The equation to solve for optimal biomass (X^*) under discounting is

$$G'[X^*] - \frac{c'[X^*]\ G[X^*]}{p - c[X^*]} = \delta; \tag{12}$$

Table 3
Cost per Trap-Haul[a] for the Northwestern Hawaiian Islands Lobster
Fishery, 1986–1988

Cost Category	Cost per Trap-Haul		
	1986	1987	1988
(1) Fleet average	4.99	4.51	4.29
(2) Minimum (Class II)	3.40	3.53	3.52
(3) Labor opportunity cost adjustment (Class II)	3.53	3.04	2.97

[a] Calculated in U.S. dollars as (1) fleet average cost, (2) minimum cost for Class II vessels (most efficient), and (3) labor opportunity cost-adjusted minimum cost per trap-haul when opportunity cost of labor is at open access equilibrium levels of fishing effort.

where $G[X]$ is the natural growth rate of lobster biomass (X), δ is the real annual discount rate, and $c[X] = c/(qX)$ is the cost of catching one unit of biomass when the present biomass is X.

In the Schaefer and Schnute models, as specified by Clark (1985),

$$G[X] = rX (1 - X/K), \tag{13}$$

and for the Fox and CY&P models,

$$G[X] = rX \ln(K/X). \tag{14}$$

Optimal biomass can be determined in the logistic model by

$$X^* = \frac{1}{4}\left(\overline{X} + K\left(1 - \frac{\delta}{r}\right) + \sqrt{\left(\overline{X} + K\left(1 - \frac{\delta}{r}\right)\right)^2 + \frac{8K\overline{X}\delta}{r}}\right). \tag{15}$$

Optimal biomass for the Gompertz model can be determined iteratively by

$$\ln\left(\frac{K}{X^*}\right) - \left(1 + \frac{\delta}{r}\right)\left(1 - \frac{\overline{X}}{X^*}\right) = 0, \tag{16}$$

which was derived from Equations 12 and 14 by using elementary calculus. Once the values for optimal biomass have been determined for an appropriate range of discount rates, then optimal yield ($G[X^*]$) and optimal effort (E^*) can be determined by

$$E^* = \frac{G[X^*]}{qX^*}. \tag{17}$$

For the Threshold model, the natural growth rate G cannot be expressed explicitly in terms of X^*. Instead, E^* is determined from a modification of Equation 12 (Appendix B). Our derivation involves an iteration of E^* instead of X^*, with E^* determined iteratively from the equation

$$\frac{k}{\dfrac{kE^*}{G[E^*]} - \dfrac{1}{A - G[E^*]}} + \frac{c}{p - \dfrac{cE^*}{G[E^*]}} = \frac{\delta G[E^*]}{q(E^*)^2}, \tag{18}$$

where

$$G[E^*] = A - B\,e^{-kE^*}. \tag{19}$$

The catchability coefficient q is assumed to be k in the Threshold model.

Results

The Schaefer, Schnute, Fox, and CY&P production models are estimated using OLS with 1982–1989 catch and effort data (from Table 1):

Schaefer:

$$(\overline{U}_{n+1} - \overline{U}_{n-1})/(2\overline{U}_n) = 0.672 - 0.277\,\overline{U}_n - 4.66 \times 10^{-7}\,\overline{E}_n.$$

t-statistic   (2.62) (−3.02)   (−3.18)*

$R^2 = 0.78$ R^2-bar $= 0.64$ DW $= 2.01$ D-h $= -0.00644$*

Schnute:[#]

$$\ln(\overline{U}_{n+1}/\overline{U}_n) = 1.43 - 0.512(\overline{U}_n + \overline{U}_{n+1})/2 - 9.13 \times 10^{-7}(\overline{E}_n + \overline{E}_{n+1})/2.$$

t-statistic   (4.75)** (−5.25)**   (−5.01)**

$R^2 = 0.90$ R^2-bar $= 0.84$ DW $= 3.04$ D-h $= -1.31$*

Fox:

$$(\overline{U}_{n+1} - \overline{U}_{n-1})/(2\overline{U}_n) = 0.312 - 0.390\ln(\overline{U}_n) - 3.76 \times 10^{-7}\,\overline{E}_n.$$

t-statistic   (1.77) (−2.48)   (−2.55)

$R^2 = 0.71$ R^2-bar $= 0.52$ DW $= 1.80$ D-h $= 0.266$*

CY&P:[#]

$$\ln(\overline{U}_{n+1}) = 0.583 + 0.437\ln(\overline{U}_n) - 2.80 \times 10^{-7}(\overline{E}_n + \overline{E}_{n+1}).$$

t-statistic   (4.37)* (4.49)*   (−4.92)**

$R^2 = 0.98$ R^2-bar $= 0.97$ DW $= 2.92$ D-h $= -1.16$*

* $P = 0.05$

** $P = 0.02$

[#] $= 1$ iteration of Cochrane-Orcutt procedure for serial correlation.

All models, with the exception of the Fox, have coefficients with the proper signs and *t*-statistics significant at the 5% level or better. The Durbin-Watson test for autocorrelation was applied, but the number of observations is insufficient to determine whether a significant problem exists (Pindyck and Rubinfeld, 1981).

Therefore we applied the Durbin h test to the Schaefer and Fox models and the results support the null hypothesis of zero first-order autocorrelation. The Durbin h-statistic detected autocorrelation in the Schnute and CY&P models. The Cochrane-Orcutt procedure (Wittink, 1988) was applied as a correction to these models (Table 4a).

The highest reported catch level for each individual species (Table 1)—1.85 million combined spiny and slipper lobsters—is used initially for A in the Threshold model. Iteration of A to maximize R^2 fails to converge to a value that we believe is realistic for the fishery. Therefore, A is increased iteratively until the improvement in the R^2 value is only 1% as proposed by Sathiendrakumar and Tisdell (1987).

The Threshold model of the NWHI lobster fishery is estimated as

$$\ln(1,900,000 - C) = 14.62 \quad - \quad 1.85 \times 10^{-6} \, E.$$

t-statistic $\qquad\qquad\qquad\qquad (27.0)^{****} \, (-2.82)^*$

* $\quad P = 0.05$

**** $P < 0.001$

This can be rewritten as $C = 1,900,000 - e^{(14.62-0.00000185E)}$, with k equal to 1.85 $\times 10^{-6}$ and B equal to 2,233,112.

Estimates of parameters r, q, and K for each model are given (Table 4a) along with statistics showing the relative fit of these models to the time series data. Because of the complex structure of the four models, exact variances of K could not be obtained, and therefore the standard deviations of the alternative estimates of MSY could not be calculated. Standard deviations of r, q, K, MSY and effort

Table 4A

Values of Parameters Estimated by the Schaefer, Schnute, Fox, CY&P, and Threshold Models for the Northwestern Hawaiian Islands Lobster Fishery

Parameter	Schaefer	Fox	Schnute	CY&P	Threshold
r	0.67	0.39	1.43	0.79	—
q	$4.66 * 10^{-7}$	$3.76 * 10^{-7}$	$9.13 * 10^{-7}$	$7.83 * 10^{-7}$	—
k	—	—	—	—	$1.85 * 10^{-6}$
K	5,220,226	5,918,398	3,050,615	3,574,015	—
B	—	—	—	—	2,233,112
A	—	—	—	—	1,900,000
R^2	0.78	0.71	0.90	0.98	0.57
R^2adj.	0.64	0.52	0.84	0.97	0.50
D-W[a]	2.01	1.80	3.04	2.92	1.09
Durbin h	-0.006^{**}	0.27^{**}	-1.31^{**}	-1.16^{**}	—
df	3	3	3	3	6

** No serial correlation at 5% level.
[a] Not sufficiently sensitive with $n = 6$.
r = intrinsic growth in year^{-1}.
q = catchability in trap-hauls^{-1}.
k = Threshold catchability in trap-hauls^{-1}.
K = maximum biomass in number of legal lobsters.
B = Threshold virgin biomass in number of legal lobsters.
A = Threshold catch estimate in number of legal lobsters.

at MSY were obtained from bootstrapping (Efron and Tibshirani, 1986) using the Shazam statistical package (White *et al.* 1990). Sampling with replacement was applied to the residuals of the regression used to test each model and a bootstrap sample was created. Another regression was then performed on the bootstrap sample which provided new estimates of *r*, *q*, *K*, MSY, and effort at MSY. This procedure was performed a thousand times and the mean, standard deviation, and coefficient of variation of each parameter were calculated (Table 4b). Based on the coefficients of variation, instability was found in MSY for the Schnute model and in parameter *K* and effort at MSY for the Fox and Schnute models. Although the CY&P and the Schaefer models performed well, the results should be tempered because of the small sample size.

The yield-effort curves for all five models are shown in Figure 2. The inclusion of price and cost information in the production equations for the Schnute, CY&P, and Threshold models is depicted in Figure 3, along with the relative positions of MEY and OAE effort levels.

The four non-asymptotic models (Schaefer, Fox, Schnute, and CY&P) predict

Table 4B

Means, Standard Deviations (STD) and Coefficients of Variation (CV) of the Bootstrap Estimates (n = 1000) of Parameters *r*, *q*, *K*, MSY and Effort at MSY in the Schaefer, Schnute, Fox and CY&P Models for the Northwestern Hawaiian Islands Lobster Fishery

Model	Parameter	Mean	STD	CV
CY&P	*r*	0.94	0.37	0.40
	q	9.19×10^{-7}	3.63×10^{-7}	0.39
	K	3,545,500	1,391,800	0.39
	MSY	1,069,500	170,750	0.16
	E(MSY)	1,058,700	341,180	0.32
Schnute	*r*	1.40	0.63	0.45
	q	9.13×10^{-7}	3.72×10^{-7}	0.41
	K	1,537,800	75,924,000	49.37
	MSY	1,172,300	4,459,000	3.80
	E(MSY)	818,880	2,214,000	2.70
Fox	*r*	0.39	0.16	0.41
	q	3.80×10^{-7}	1.48×10^{-7}	0.39
	K	6,373,500	9,783,000	1.53
	MSY	845,530	495,410	0.59
	E(MSY)	1,012,000	1,587,500	1.57
Schaefer	*r*	0.67	0.26	0.39
	q	4.65×10^{-7}	1.50×10^{-7}	0.32
	K	5,716,100	2,309,100	0.40
	MSY	854,070	190,360	0.22
	E(MSY)	714,720	143,440	0.20

r = intrinsic growth in year^{-1}.
q = catchability in trap-hauls^{-1}.
K = maximum biomass in number of legal lobsters.
MSY = maximum sustainable yield in number of legal lobsters.
E(MSY) = fishing effort in trap-hauls at *MSY* level of production.

MSY within a 22% range for this fishery (Table 5). Effort levels at MSY are predicted within a 30% range for the four models, while estimated profits at MSY vary 70% because of differences in predicted effort. Predictions of MSY for the Threshold model are not relevant because the model uses an asymptotic maximum.

The five models show considerable differences in predicted optimums, *i.e.*, MEY and effort. The MEY varies by as much as 54% while corresponding effort varies by as much as 47%. Profit at MEY varies by 60%. Large differences also exist between the Threshold and other models for predicted yield at OAE. The Threshold model predicts a yield almost three times that of the Schaefer model, whereas the non-asymptotic models estimate both yield and effort levels within 28%. These substantial differences demonstrate clearly the importance of model choice.

Discounted optimal values for Y^*, E^*, X^*, and U^*, along with estimates of resource rent ($TR - TC$, where TR is total revenue) are shown in Table 6. The discount rates are representative of biological considerations (1% and 5%), social accounting (10%), and private interest rates compounded by risk (25%) (Clark 1985). Model results at 0% (no discounting) and ∞ confirm values estimated for static MEY and OAE (Table 5). All models show the same trends over the relevant range (i between 0% and 25%) although absolute values vary. On a percentage basis, estimated optimal effort values vary the most over alternative interest rates within a model (5-24%), while estimated resource rents (*i.e.*, estimated profit, not including consumer and producer surpluses) vary the least (0-7%). The MEY varies most in the Fox model (11%) and least in the Threshold model (2%). Optimal biomass levels and optimal catch per trap-haul vary by only 3-14%.

Discussion

Each of the models examined in the previous section—Fox, Schaefer, Schnute, CY&P, and Threshold—appears to estimate valid biological parameters and rea-

Table 5
Static Biological Equilibrium (MSY), Economic Optimum (MEY), and Economic Equilibrium (OAE) for the Northwestern Hawaiian Islands Lobster Fishery[a]

	Schaefer	Fox	Schnute	CY&P	Threshold
			MSY		
Y	877,947	850,015	1,088,219	1,040,393	—
E	722,396	1,039,200	781,595	1,011,195	—
$	1,849,144	781,144	2,630,060	1,730,540	—
			MEY		
Y	814,632	708,127	1,028,422	919,867	1,547,224
E	528,398	530,765	598,379	588,741	997,299
$	2,137,231	1,645,604	2,902,134	2,436,835	4,077,892
			OAE		
Y	689,821	831,376	781,181	960,400	1,889,460
E	1,056,796	1,273,656	1,196,758	1,471,320	2,894,627
$[b]	0	0	0	0	0

[a] Price equals $4.55/lobster and cost is $2.97/trap-haul ($Y$ = number of legal lobsters; E = trap-hauls; $ = *net* revenue in 1989 U.S. dollars).
[b] By definition, at OAE, profit is equal to zero.

Table 6

Optimal Values for Yield (Y^*), Fishing Effort (E^*), Biomass (X^*), Profit (p), and Catch per Unit Effort (U^*) for the Northwestern Hawaiian Islands Lobster Fishery, with Different Interest Rates (i)

Model	i	Y^*	E^*	X^*	p	U
Schaefer	0	814,632	528,398	3,311,054	2,137,231	1.54
	1	818,570	534,529	3,288,903	2,136,944	1.53
	5	832,408	557,871	3,204,565	2,130,582	1.49
	10	845,995	584,582	3,108,055	2,113,069	1.45
	25	869,350	650,908	2,868,410	2,022,345	1.34
	50	877,893	728,089	2,589,542	1,831,987	1.21
	∞	689,821	1,056,796	1,400,746	0	0.65
Fox	0	708,127	530,765	3,551,329	1,645,604	1.33
	1	713,921	539,760	3,520,723	1,645,254	1.32
	5	734,164	573,236	3,409,116	1,637,934	1.28
	10	754,163	610,135	3,290,190	1,619,338	1.24
	25	792,155	696,224	3,028,611	1,536,521	1.14
	50	821,111	789,271	2,769,223	1,391,921	1.04
	∞	831,376	1,273,656	1,736,031	0	0.65
Schnute	0	1,028,422	598,379	1,882,858	2,902,134	1.72
	1	1,030,604	601,752	1,876,275	2,902,042	1.71
	5	1,038,648	614,779	1,850,854	2,899,955	1.69
	10	1,047,327	630,085	1,820,984	2,893,987	1.66
	25	1,066,209	670,440	1,742,230	2,860,047	1.59
	50	1,082,217	723,551	1,638,582	2,775,143	1.50
	∞	781,181	1,196,758	714,948	0	0.65
CY&P	0	919,867	588,741	1,996,641	2,436,835	1.56
	1	923,231	593,940	1,986,403	2,436,701	1.55
	5	935,542	613,792	1,947,784	2,433,751	1.52
	10	948,707	636,676	1,904,200	2,425,687	1.49
	25	977,505	694,848	1,797,747	2,383,951	1.41
	50	1,004,745	767,141	1,673,708	2,293,179	1.31
	∞	960,400	1,471,320	833,649	0	0.65
Threshold	0	1,547,224	997,299	—	4,077,892	1.55
	1	1,548,737	999,622	—	4,077,877	1.55
	5	1,554,571	1,008,673	—	4,077,539	1.54
	10	1,561,405	1,019,473	—	4,076,559	1.53
	25	1,579,342	1,048,889	—	4,070,806	1.51
	50	1,602,847	1,090,032	—	4,055,558	1.47
	∞	1,889,460	2,894,627	—	0	0.65

sonable economic results for the NWHI lobster fishery. All the models except the Fox model have statistically significant coefficients, but because of the iterative procedure used, the statistical results for the Threshold model have been forced. The Threshold model's estimates contrast markedly with those of the other models. Although this contrast was expected because of the Threshold model's underlying assumptions, we believed it necessary to explore its potential as a viable model for this fishery.

The CY&P model has the best fit with the data ($R^2 = 0.98$) while the Schnute has the strongest t-statistics ($P < 0.02$). The logistic models (Schaefer and Schnute) have a strong body of theoretical literature supporting their applicability to fishery science, whereas models using the Gompertz curve (*e.g.*, the Fox model) apparently have less acceptance.

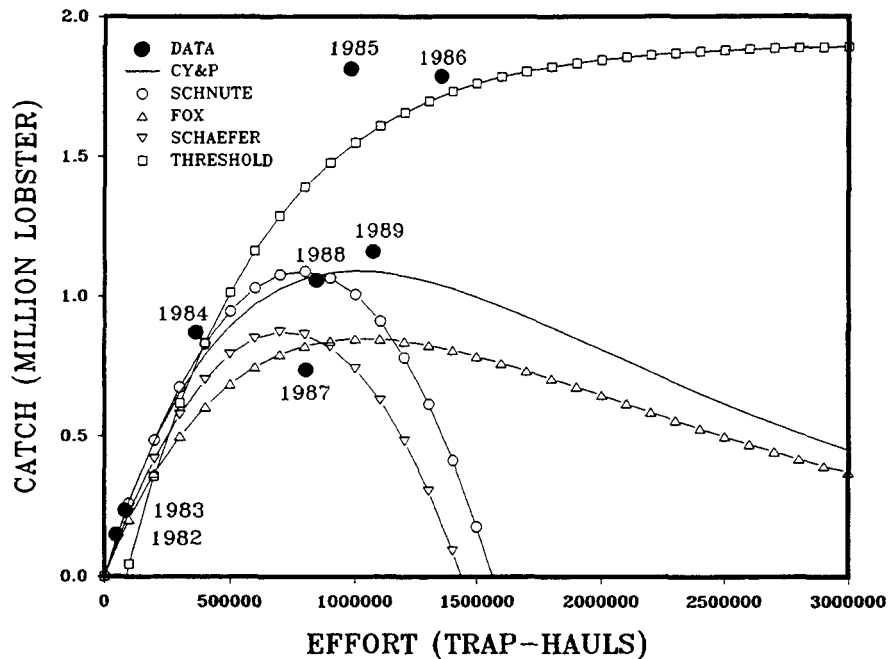The choice between the finite difference (Schaefer and Fox) or integrated

Figure 2. Yield-effort relationships for the Schaefer, Schnute, Fox, CY&P, and Threshold models.

(Schnute and CY&P) models to estimate biological parameters from time series catch and effort data appears to involve a debate over whether the CPUE data employed represent an annual or instantaneous estimate of relative abundance (Pella and Tomlinson, 1969; Schnute, 1977). We believe that the integrated models are theoretically stronger and should be used for the NWHI lobster fishery because of the trends in actual effort and CPUE. For a more complete discussion of dynamic models, see Schnute (1989).

Validation of the CY&P by independent estimates is difficult. Clarke and Pooley (1988) have shown that in aggregate the NWHI commercial lobster fleet broke even during 1986 while expending 1.35 million trap-hauls. If this level of effort is assumed to be approximately representative of OAE, the Fox and CY&P models predict OAE effort accurately. Using similar cost-earnings data and a simple linear CPUE and effort relationship, Samples and Sproul (1987) estimated MEY in the NWHI commercial lobster fishery based on Class II vessels at 893,000 trap-nights with potential economic profits of $2.33 million. While their estimate of economic profit appears to agree with the values from the CY&P and Schaefer models, predicted effort is different, even when corrected for differences between the effort variables, trap-night versus trap-hauls (cf. Clarke and Todoki, 1988). The MEY predicted by each of our models, with the exception of the Threshold model, falls between 528,000 and 599,000 trap-hauls, substantially less than that predicted by Samples and Sproul (1987). The Fox model is the most conservative and thus deviates the most from their prediction.
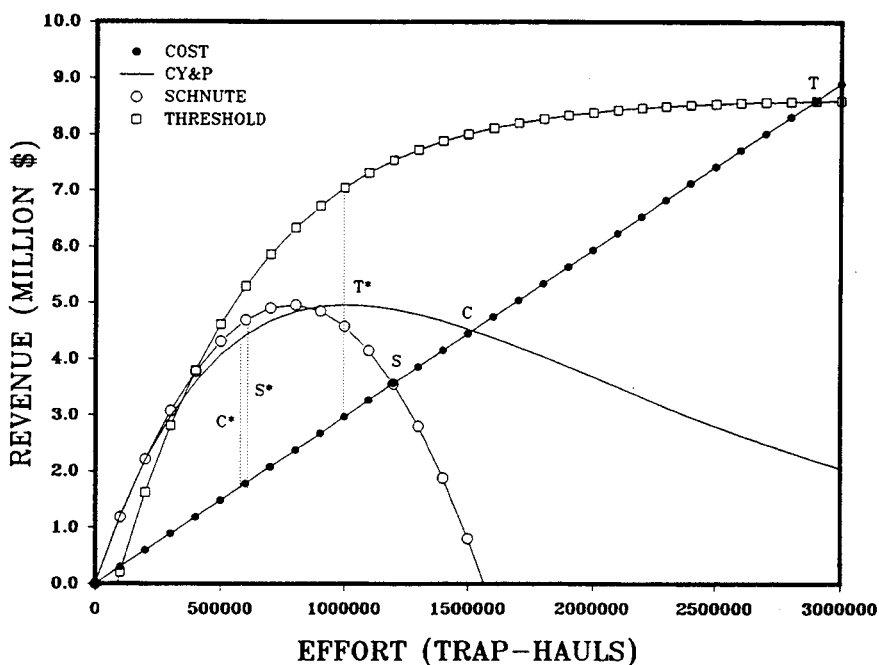
Figure 3. Revenue-effort and cost functions for the Northwestern Hawaiian Islands lobster fishery, using the Schnute (S), CY&P (C), and Threshold (T) models (S, C, and T = the effort levels for open access equilibrium; S*, C*, T* = the net revenue and fishing effort levels for maximum economic yield).

Polovina and Moffitt (1989), using different procedures, estimated MSY for the fishery at 1.14 million spiny and slipper lobsters from 848,000 trap-hauls. The Schnute model best approximates this value in terms of yield (1.1 million), but predicts lower effort levels to obtain the given yield (780,000 trap-hauls). According to Polovina and Moffitt (1989), the yield for 1988 (1.1 million combined spiny and slipper lobsters) falls within the 95% confidence intervals of their model. However, from a bioeconomic point of view, profits (with crews accruing some of the rent) have been estimated at $1.2 million for the fishery in the same year (Clarke, 1989). This estimate of resource rent (profit) is substantially less than that predicted at MSY effort levels and more in line with that predicted by the CY&P model.

Significant differences in results also are due to the choice of cost estimate (Table 3). These differences are summarized in Table 7. If the CY&P model and the labor opportunity cost adjusted average minimum class II cost ($2.97 per trap-haul) are used, then fleet profits at MSY are $1.7 million and resource rent at MEY is $2.4 million. MEY occurs at 589,000 trap-hauls (919,000 lobsters). With the average minimum class II costs ($3.52 per trap-haul), without the labor opportunity cost adjustment, profits at MSY drop to $1.2 million, and MEY is estimated to occur at 536,000 trap-hauls yielding 882,000 lobsters, with potential resource rent of $2.1 million. Using the fleet average cost per trap-haul ($4.29),

Table 7

Differences in Resource Rent at Maximum Economic Yield (MEY) and Fleet
Profit at Maximum Sustainable Yield (MSY) with Alternative Cost Parameters
for the Northwestern Hawaiian Islands Lobster Fishery Using the CY&P
Model. Million U.S. Dollars

Cost Alternative[a]	Rent (MEY)	Profit (MSY)
(1) Fleet average	1.7	0.4
(2) Minimum (Class II)	2.1	1.2
(3) Labor opportunity cost (Class II)	2.4	1.7

[a] (Table 3)

fleet profits at MSY drop to $396,000, and MEY effort is 469,000 trap-hauls,
yielding 824,977 lobsters and a potential resource rent of $1.7 million.

The effects of discounting on the models appear to be universally limited for
the results presented. All models show that the resource rent will change negli-
gibly even when discounted effort levels may vary as much as 24% over the
relevant range. The MEY and associated resource rent are relatively insensitive to
choice of discount rates. These results are supported by studies that suggest
fisheries management policy is often insensitive to changes in the discount factor
over a range of values likely to be found in practice (*e.g.*, Mendelssohn, 1982).

The open access CPUE levels converge to 0.65 for all models as expected,
because of the theoretical importance of cost-price ratios in establishing OAE
(Clark, 1985). If the minimum fleet average cost per trap-haul ($2.97) and the 1988
price ($4.74 per lobster) are used, then CPUE levels at OAE converge at 0.63,
which is essentially the same as the ratio of the minimum cost per trap-haul ($2.97)
to the average 1986–1988 ex-vessel price ($4.55) per lobster. Despite the fact that
all major banks had been extensively fished, the OAE CPUE values are substan-
tially below the catch rates exhibited in the fishery over the past 3 years of
intensive fishing effort.

Although the CY&P model appears to have a strong fit and validated results,
its appropriateness must be tempered. The analysis of the fishery is of one unit
stock rather than separating the two major species, spiny and slipper lobster. At
the same time, there is noticeable, if not quantifiable, targeting by the fleet as a
whole and by segments of the fleet on different species. If a model that integrates
the economic and biological differences of the two species were developed, it
would more accurately reflect the bioeconomics of the fishery. Presumably size
measures could be altered to reflect such differences, or there could be species-
specific quotas (either fleet-wide or individual vessel).

Conclusion

With rapidly developing, high-value fisheries such as the NWHI lobster fishery,
resource managers have limited research dollars and yet are forced to make man-
agement decisions based on relatively limited biological and economic data. Sur-
plus production models are useful in such situations because of their relatively
limited data requirements, although some (*e.g.*, Townsend 1986) question their
applicability.

All of the models explored show reasonable results, but the CY&P model appears to be the best for economic analysis in the NWHI lobster fishery. This conclusion is tempered by the relatively short time series of data used and the fact that our data set is limited to the ascending limb of the yield-effort relationship. However, Yoshimoto and Clarke (*in press*) applied this model to other lobster catch and effort data and found the CY&P model has an equal or better fit and robustness than the other integrated model explored (Schnute). These fisheries provided substantially longer time series of CPUE data (New Zealand rock lobster, 1945–1987; Tasmanian rock lobster, 1947–1984; American (New England) lobster, 1950–1979).

The use of integrated surplus production models (Schnute and CY&P) as compared to the more conventionally applied Schaefer and Fox finite difference models would allow more liberal effort rates in the NWHI lobster fishery, as well as predicting higher levels of revenue at the economic optima (MEY). However, this may not always be the case and would depend on the catch-effort relationship of the specific fishery for which they are applied. As for the comparison between the integrated models, Schnute (1977) points out that a problem with his model is that the predicted variable, $\overline{U}_{n+1}$, appears on both sides of the regression equation and it is not clear which term should be regressed on $(\ln(\overline{U}_{n+1}/\overline{U}_n)$ or $(\overline{U}_n + \overline{U}_{n+1})/2)$. As a result, better regression fits are expected from the CY&P model since its functional form is more straightforward than that of the Schnute model.

Each of the models tested for the NWHI lobster fishery demonstrates that, although the combined yield of spiny and slipper lobsters was not excessive biologically, capital inputs must be adjusted downward if resource rents or profits are to be maximized in the future. The NWHI lobster fishery for 1987–1989 was within MSY norms (given that no data are available on species targeting by fishermen), but by the reference points of the CY&P model, fishing effort has exceeded MEY (assuming "fishing up" has been completed). In the absence of evidence of biological overfishing on the combined stocks and no means of capturing resource rents when restricting effort to MEY levels, there was little likelihood of the adoption of access limitations or individual transferable quotas in order to optimize the fishery economically. Indeed, many participants in the fishery clearly expressed their hostility to effort regulation in 1987–1988 despite the fishery's approach to OAE in 1986. The diminished effort in 1987–1988 suggested that, to a certain extent, the fishery could be self-regulating. Cost-earnings data on vessel operation and performance appeared to confirm our hypothesis that the fishery may be self-regulating. Also supporting this hypothesis are the relatively large investments needed to gear up for fishing and the potentially catastrophic financial results of a shortened or poor trip (Clarke and Pooley 1988).

On the other hand, exogenous events do exist and are as near at hand as the recent, rapid expansion of the Hawaii longline fleet and as distant as the diminishing yields in the Bering Sea, Gulf of Alaska, and Gulf of Mexico fisheries, any of which could bring a large influx of new vessels into the NWHI lobster fishery. The effects of a substantial increase in effort can only be surmised from the models presented. Not surprisingly, faced with the prospect of renewed participation by vessels from Hawaii's other fisheries (*e.g.*, tuna and swordfish longliners), interest in limited entry returned. The limitations of fishery-wide stock production models were also revealed by the apparent recruitment (or catchability) crisis in 1989–90. However, the logistics of regulation and enforcement appear to

mitigate against any bank-by-bank approach to fisheries management. Therefore, assiduous monitoring and evaluation of the key economic and biological signals available in this fishery, including informal information from vessel owners and operators, remain important.

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Appendix A

Derivation of the CY&P Model

Substituting $X = U/q$ into Equation 3 and multiplying both sides by q/U gives

$$(1/U) \, dU/dt = r \ln(qK) - r \ln(U) - qE.$$

Integrating from $t =$ year n to $t =$ year $n + 1$ yields

$$\ln(U < n + 1 >/U < n >) = r \ln(qK) - r \int_{t=n}^{n+1} \ln(U)dt - q\overline{E}_n; \quad \text{(A1)}$$

where $U\langle n \rangle$ is the instantaneous CPUE at the start of year n, and E_n is the total effort for year n.

The first degree Taylor polynomial for $\ln(U)$ centered at $\overline{U}_n$, the average CPUE for year n, is

$$\ln(U) \approx \ln(\overline{U}_n) + (1/\overline{U}_n)(U - \overline{U}_n)$$

$$= \ln(\overline{U}_n) - 1 + (U/\overline{U}_n).$$

Integration of this approximation yields

$$\int_n^{n+1} \ln(U)dt = \ln(\overline{U}_n) - 1 + (1/\overline{U}_n) \int_n^{n+1} Udt. \quad \text{(A2)}$$

By definition, $\overline{U}_n = \int_n^{n+1} Udt$, so Equation A2 becomes

$$\int_n^{n+1} \ln(U)dt = \ln(\overline{U}_n) - 1 + 1 = \ln(\overline{U}_n).$$

Putting this result into Equation A1 gives

$$\ln(U\langle n + 1 \rangle / U\langle n \rangle) = r \ln(qK) - r \ln(\overline{U}_n) - q\overline{E}_n.$$

Adding this equation to its corresponding $(n + 1)$th equation gives

$$\ln((U\langle n + 2 \rangle U\langle n + 1 \rangle)/(U\langle n + 1 \rangle U\langle n \rangle)) = 2r \ln(qK) - r(\ln(\overline{U}_n) + \ln(\overline{U}_{n+1}))$$
$$- q(\overline{E}_n + \overline{E}_{n+1}). \quad \text{(A3)}$$

We use Schnute's (1977) assumption to estimate for instantaneous CPUE

$$\overline{U}_n = SQRT(U\langle n + 1 \rangle U\langle n \rangle);$$

that is, the CPUE of a given year is the geometric mean of the CPUE's at the beginning and ending of that year. Plugging this estimate of CPUE into Equation A3 and solving algebraically for $\ln(\overline{U}_{n+1})$ gives

$$\ln(\overline{U}_{n+1}) = (2r/(2 + r)) \ln(qK) + ((2 - r)/(2 + r)) \ln(\overline{U}_n)$$
$$- (q/(2 + r))(\overline{E}_n + \overline{E}_{n+1}).$$

The results of the above equation are dependent on how good an approximation the Taylor polynomial gives. If instantaneous values of CPUE for a given year, n, are suspected to fluctuate considerably away from $\overline{U}_n$, the Taylor approximation becomes invalid and another method to estimate the integral of $\ln(U)$ is needed. As a crude indicator of how reasonable the approximation is, average monthly CPUEs ($\overline{u}_k$ denotes the average monthly CPUE for month k) are assumed to be representative of the instantaneous CPUEs for a given year. The terms $\ln(\overline{u}_k)$ and $(\ln(\overline{U}_n) - 1 + \overline{u}_k/\overline{U}_n)$ are summed for a given year, n, divided by 12, and compared:

Year	$\left(\displaystyle\sum_{k=1}^{12} \ln(\overline{u}_k)\right)\Big/ 12$	$\left(\displaystyle\sum_{k=1}^{12} A_k\right)\Big/ 12$	% Error
1983	1.08	1.13	+4.60
1984	1.27	1.30	+1.90
1985	0.93	0.95	+2.19
1986	0.62	0.64	+2.26
1987	0.27	0.31	+14.95
1988	0.50	0.55	+9.52

Note: $A_k = \ln(\overline{U}_n) - 1 + \overline{u}_k/\overline{U}_n$.

The Taylor approximation appears to introduce relatively small errors, and its use with the above data appears warranted.

Appendix B

Derivation of Discounting for the Threshold Model

From the Threshold model, with catch written as G

$$\ln(A - G) = \ln(B) - kE$$
$$= \ln(B) - kG/(qX).$$

Taking the derivative (with respect to X) of both sides:

$$(-1/(A - G))G'[X] = -k/q((1/X)G'[X] - G/X^2).$$

Solving for $G'[X]$

$$G'[X] = \frac{kG/(qX^2)}{k/(qX) - 1/(A - G)} .$$

Inserting $G'[X]$ and $c'[X] = -c/(qX^2)$ into Equation 12 yields

$$\frac{kG/(q(X^*)^2)}{k/(qX^*) - 1/(A - G)} + \frac{cG/(q(X^*)^2)}{p - c/(qX^*)} = \delta.$$

Multiplying both sides by $q(X^*)^2/G$ yields

$$\frac{k}{k/(qX^*) - 1/(A - G)} + \frac{c}{p - c/(qX^*)} = \frac{\delta q(X^*)^2}{G} .$$

Plugging in $G/(qE^*)$ for X^* gives Equation 18 in the text.