Why Harvest Efficiency Appears to Fall Over Time in the Production Functions of Fisheries

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Abstract

Harvest efficiency in the production functions of fisheries should increase over time with the introduction of new technology and with increasing knowledge of the biology and behaviour of the target species. This implies that the estimated catchability coefficients of Gordon - Schaefer or Fox models should also increase over time. We estimated both models using annual catch and effort data for four lobster fisheries and compared the regression results for different time periods. We also estimated modified forms of the models with a time trend in the harvest equation. Both approaches show that the estimates of the catchability coefficients have decreased significantly over time in all four fisheries. We suggest that one important source of this anomaly is the use of annual aggregate catch and effort data. To test this hypothesis, we examined trends in the distribution of effort over the season, and their effect on annual catch per unit effort. The results show that methods based on aggregate annual catch and effort data can introduce spurious trends in annual catch per unit effort, and hence in catchability estimates. Estimation of production functions for bioeconomic modelling should use catch and effort data that is disaggregated both temporally and spatially.

Keywords: Fisheries ; production functions ; bioeconomic models ; catchability

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1. Introduction

In this research we have used time series data for four lobster fisheries to examine the empirical performance of production functions of the surplus yield type. We looked at the Schaefer and Fox models, and a number of extensions to these models. Our intention was to assess whether the models incorporate adequate biological relationships, and are sufficiently tractable to permit rigorous empirical analysis within a bioeconomic framework. An unexpected result of this analysis was that the estimated ca· ʰability coefficient, and by implication the harvest efficiency, appears to be falling over time in all four fisheries.

Surplus yield models incorporate the stock externality into bioeconomic analysis by including dynamic biological relationships in the production function. Section 2 describes the most commonly used forms, namely the Gordon/Schaefer (Gordon 1954; Schaefer 1954; Schaefer 1957) and Fox (1970) models. The Gordon/Schaefer model uses a logistic growth equation, while the Fox model uses a Gompertz growth equation. Section 2 also describes a technique introduced by Schnute (1977) which simplifies empirical analysis using both the Schaefer and Fox models. This technique requires only catch and effort data, and has been used extensively by both economists and biologists. More recently, biologists and fishery managers have largely abandoned the use of surplus yield models for the reasons given in section 2.6. However, economists still use them to investigate the determinants of sustainable equilibrium conditions in fisheries.

Section 3 gives a brief description of four invertebrate fisheries, and presents and discusses the annual catch and effort data for the fisheries. In Section 4 we introduce the monthly catch and effort data for the Western Rock Lobster fishery. During the history of the fishery there has been a marked change in the distribution of effort over the season. Section 5 presents the results from empirical analysis of the models presented, using data for the example fisheries. The results, including the anomalous negative trend in

catchability, are discussed in section 6. We present a partial explanation using the monthly data.

2. The Surplus Yield Model

2.1 The Gordon-Schaefer Model

Equations (1) to (3) show the structure of the production function in the Gordon - Schaefer model (Gordon 1954; Schaefer 1954; Schaefer 1957). The stochastic term is omitted.

$$(1) \quad X_{t+1} - X_t = r \cdot X_t \left[1 - \frac{X_t}{k}\right] - H_t$$

$$(2) \quad H_t = q \cdot E_t \cdot X_t$$

$$(3) \quad R_t = \frac{H_t}{E_t} = q \cdot X_t$$

The variable X_t is total biomass in year t. H_t is the level of harvests or catches by weight, and E_t is the level of fishing effort applied (eg pot lifts). The first term in equation (1) represents natural growth in biomass as a logistic function of the lagged stock. This implies that natural mortality, growth and reproduction are density dependent. The parameter k is the average stock size that would occur in the absence of fishing, and is sometimes known as the ceiling stock size. The parameter r is the intrinsic natural growth rate. The second term in equation (1) is annual fishing mortality, defined in equation (2) as a linear function of current biomass and the level of fishing effort applied. The coefficient q is a fixed coefficient of catchability. Identity (3) defines the term "catch per unit effort", CPUE or R_t, which is a proxy for biomass. This identity is included because population biomass X_t is not observable and is usually very difficult to estimate.

In the absence of fishing, the population biomass of the target species would vary stochastically about an average stock size k. In the event of a single shock, the biomass would approach k asymptotically. The effect of fishing at a constant sustainable level is to progressively reduce the average biomass to an equilibrium level lower than k.

Schnute (1977) proposed a method for estimating this model using only catch and effort data. This method involves substituting equation (3) into equation (1) to obtain either of the reduced forms in equations (4) or (5).

$$(4) \quad R_{t+1} - R_t = r \cdot R_t - \frac{r}{q \cdot k} \cdot R_t^2 - q \cdot H_t$$

$$(5) \quad \frac{R_{t+1} - R_t}{R_t} = r - \frac{r}{q \cdot k} \cdot R_t - q \cdot E_t$$

Annual biomass and harvests will vary stochastically about average sustainable levels. Equation (6) shows the relationship between the level of effort and average sustainable yield (ASY). Differentiating equation (6) with respect to effort and setting the result equal to zero gives the level of effort required to return the maximum sustainable yield (MSY). Equations (7) and (8) show the resulting relationships. Assuming that the sale price (p) and marginal factor cost (c) are both constant, equations (9) to (11) show the estimates for marginal sustainable revenue (MR_e), optimal effort (E^*), and maximum sustainable economic rent (Π).

$$(6) \quad ASY = q \cdot k \cdot E \cdot \left(1 - \frac{q \cdot E}{r}\right)$$

$$(7) \quad E_{MSY} = \frac{r}{2 \cdot q}$$

$$(8) \quad MSY = \frac{r \cdot k}{4}$$

(9) $\quad MR_E = p \cdot q \cdot k \left(1 - \dfrac{2 \cdot q \cdot E}{r}\right)$

(10) $\quad E^* = \left(\dfrac{r}{(2 \cdot q)}\right)\left(1 - \dfrac{c}{(p \cdot q \cdot k)}\right)$

(11) $\quad \Pi = p \cdot q \cdot k \cdot E \left(1 - \dfrac{q \cdot E}{r}\right) - c \cdot E$

Note from equations (7) and (10) that, if the marginal cost is not zero, the economic optimum level of effort is unambiguously less than the effort level that generates maximum sustainable yield. The economic optimum average yield is also less than maximum sustainable yield. The extent to which E^* is less than E_{MSY} varies with the ratio of marginal factor cost to price.

2.2 The Fox Gompertz Model

In this model, the Gompertz function in equation (12) replaces the logistic growth component in equation (1). The reduced form of this model is equation (13). The relationships for average sustainable yield, maximum sustainable yield and the corresponding effort level are derived as for the Schaefer model, and the resulting equations are (14) to (16). Similarly, equations (17) and (18) show the marginal sustainable economic yield and maximum sustainable economic rent functions.

(12) $\quad X_{t+1} - X_t = r \cdot X_t \cdot (Ln\ k - Ln\ X_t) - H_t$

(13) $\quad \dfrac{R_{t+1} - R_t}{R_t} = r \cdot Ln(q \cdot k) - r \cdot Ln(R_t) - q \cdot E$

(14) $\quad ASY = q \cdot k \cdot E \cdot \exp\left(-\dfrac{q \cdot E}{r}\right)$

(15) $\quad E_{MSY} = \dfrac{r}{q}$

(16) $\quad MSY = r \cdot k \cdot \exp(-1)$

(17) $\quad MR_e = p \cdot q \cdot k \cdot \exp\left[-\dfrac{q \cdot E}{r}\right] \cdot \left[1 - \dfrac{q \cdot E}{r}\right]$

(18) $\quad \Pi = p \cdot q \cdot k \cdot E \cdot \exp\left[-\dfrac{q \cdot E}{r}\right] - c \cdot E$

The level of effort that returns the maximum sustainable economic yield is the solution for E^* in equation (19).

(19) $\quad E^* + \dfrac{c \cdot r}{p \cdot q^2 \cdot k} \cdot \exp\left(\dfrac{q \cdot E^*}{r}\right) = \dfrac{r}{q}$

The left hand side of equation (19) is greater than or equal to E^* since all parameters are positive. Therefore the optimal effort (E^*) is unambiguously less than that which yields the maximum sustainable yield, as in the Gordon - Schaefer model.

2.3 Comparison of the Gordon - Schaefer and Fox Models

For both models, the time path of adjustment after a single shock to the biomass is asymptotic. Figure 2.3.1 shows the response to a sustained disturbance, such as the introduction of fishing.
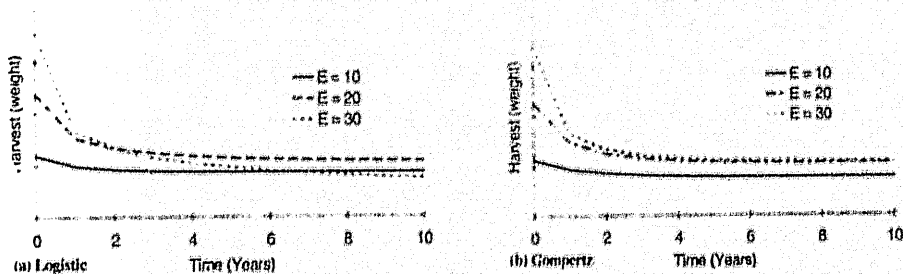

Figure 2.3.1 Schaefer (logistic) versus Fox (Gompertz). Time path of harvest after the introduction of fishing at various levels of effort.

The sustainable yield function for the Fox model (equation 14) is not symmetric, but is skewed to the right. Figure 2.3.2 compares the sustainable yield functions for logistic and Gompertz growth models with parameter values similar to those estimated for the

Western Rock Lobster. At high levels of effort, the level of harvest remains high in the case of the Gompertz production function. This implies that the level of sustainable harvest is much more robust to high effort levels than in the logistic case.
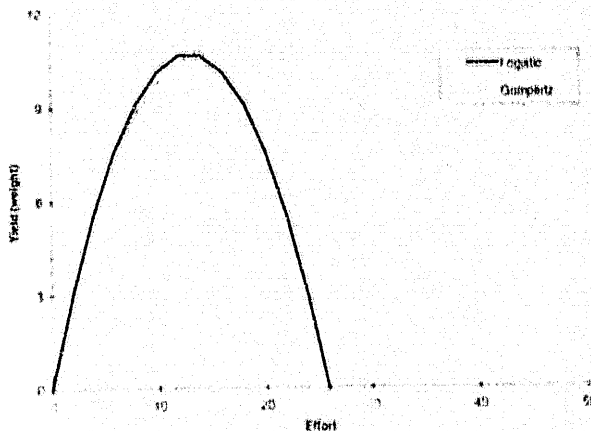

Figure 2.3.2 Comparison of the sustained yield functions for the Logistic and Gompertz models.

The skewed sustained yield function for the Gompertz (Fox) model is more realistic for many fisheries. All of the lobster species discussed in section 3 have high fecundity. Therefore the population biomass should exhibit considerable resilience in the face of fishing pressure and we would expect a skewed yield function.

2.4 Criticisms Of Surplus Yield Models

Fishery scientists cite evidence that the natural rates of growth, mortality, reproduction, and vulnerability to fishing gear vary significantly by age. They argue that growth and harvest functions based on total population biomass are unreliable. When appropriate data is available, scientists prefer growth and harvest functions based on the number of individuals of various ages or size cohorts in the population (Schnute 1987; Hall 1994). These may be incorporated in simulation models using fortnightly or monthly time intervals and small geographic areas (Walters, Hall et al. 1993, McGarvey et al. 1996).

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Furthermore, multiple regression models that include current effort and lagged indicators of the environment (or juvenile abundance) often give reliable forecasts of harvests. These models exclude the lagged impacts of past fishing mortality on the breeding stock (Orach-Meza and Saila 1978; Phillips, Cruz et al. 1994; Caputi, Chubb et al. 1995).

For all four of the lobster species investigated in this paper, the time lags from spawning to both recruitment and reproductive maturity far exceeds one year. Therefore modelling changes in current biomass as a function of biomass in the previous year *only* is unlikely to fully capture the biological effects of fishing.

Early results using Gordon – Schaefer models for some fisheries suggested a degree of success in using the models to predict optimal levels of either effort or harvest as targets for fishery managers. It has proved to be more difficult to obtain reliable estimates of the individual parameters of the models. Uhler (1980) examined the estimation technique described in section 2.1 using both theoretical analysis and Monte Carlo techniques. Under the Schaefer assumptions, and with the additional assumption of a stochastic harvest equation, Uhler showed that the technique yields heavily biased estimators for the catchability and intrinsic growth rate parameters. However, the estimators of optimal effort and harvest have a much less severe bias. Townsend (1986) examined the use of surplus yield models in the American Lobster fishery and demonstrated that the models failed to identify the downward sloping section of the yield on effort curve.

3. The Fisheries and the Data

We first applied the annual analysis described in this paper to the fishery for the Western Rock Lobster (*Panulirus cygnus*) in Western Australia. Other fisheries that we examined are the Tasmanian Rock Lobster, the New Zealand Rock Lobster and the American Lobster. Except for the American Lobster, all of these species are closely related and have similar life histories. The American Lobster is a clawed lobster, which lives in a different

type of habitat, but like the Panulirus species, is highly fecund, has extended and complex larval stages, and is relatively long-lived. All four species take several years to attain minimum legal size in the fisheries, and even longer to reach reproductive maturity.

The regulatory histories of the four fisheries differ. Limited entry was introduced into the Western Rock lobster fishery in 1963 (Meany 1979). Prior to this date, entry to the fishery had been unrestricted, with regulation limited to issues such as minimum size (since the 19th century) and measures to protect breeding lobsters. There has been a series of regulatory changes since the 1960's, including reductions in the number of licensed pots. The Tasmanian lobster fishery has a similar history with the number of vessels being restricted in 1967 and the number of pots in 1972 (Campbell 1989). By contrast, the main management measures used in the US component of the American Lobster fishery were shorter fishing seasons, minimum and maximum sizes, with few controls on entry (Miller 1995). The New Zealand Lobster fishery experienced a rapid growth in the number of participants and the level of fishing effort after World War II. The fishery management retained open access conditions until the 1980/81 season when they introduced individual tradeable quotas (ITQs). (Booth and Breen 1994).
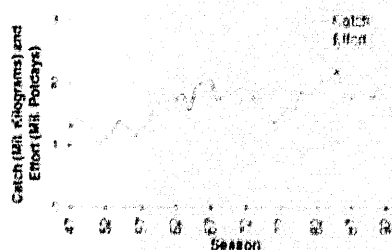
Figures 3.1 to 3.4 show the data for catch and effort in the four fisheries. In the Western Rock Lobster fishery, pots (traps) are usually lifted each day, and the effort figures are the number of potlifts. Catches are measured in kilograms and catch per unit effort (CPUE) is defined as catch in kilograms divided by the number of potlifts.
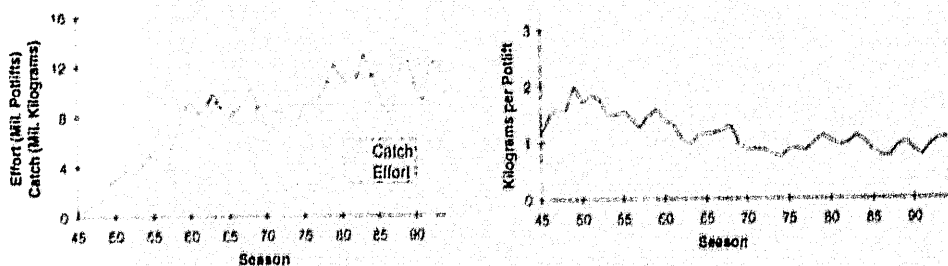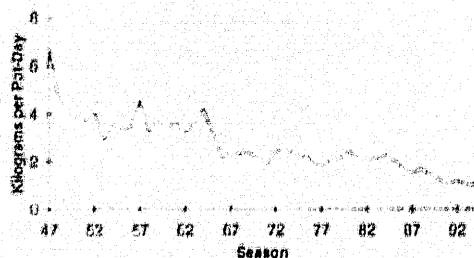

(a) Catch and effort.   (b) Catch per unit effort.

Figure 3.1 Western Rock Lobster (Data: Dr N. Caputi, Fisheries Department of Western Australia)

The graph of effort and catch in the fishery (figure 3.1a) shows rapid growth in both measures until the early 1960s. Thereafter the effort series has continued to grow, but more slowly. This growth has been possible because licence holders have been able to substitute other inputs such as faster boats, and so increase the level of effort generated by a fixed number of pot licences. The catch level graph displays a secular trend and a large variance. The trend resulted from the increased nominal level of effort and improved harvest efficiency, while the variance reflects highly variable environmental conditions. Figure 3.1b shows a downward trend in catch per unit effort, especially during the early years of the data.

The graphs for the Tasmanian Rock lobster (figure 3.2) show a very similar pattern. By contrast, the graphs for the New Zealand Lobster and the American Lobster show different histories. In New Zealand, the highest catches were achieved in the 1950s, and catches have not returned to that level despite escalating effort levels during the last three decades. After the introduction of individual tradeable quotas in 1980/81, effort continued to rise, but has since fallen, as has the size of the annual catch. The CPUE was highly variable early in the series and has fallen steadily since. We have a shorter history for the American lobster, but this shows almost constant catch levels with constantly rising effort and in consequence the CPUE has consistently fallen.
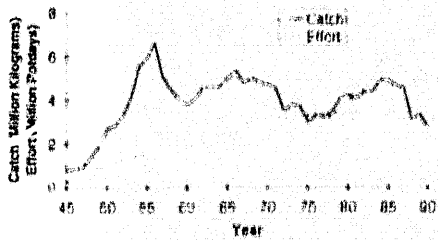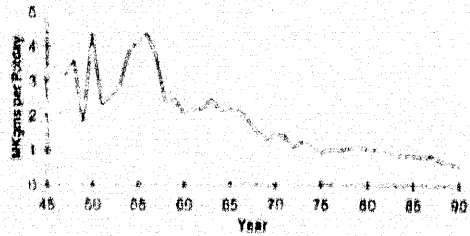

(a) Catch and effort.

Figure 3.2 Tasmanian Rock Lobster

(b) Catch per unit effort.

Data: (Campbell and Hall 1988) and Professor Campbell.
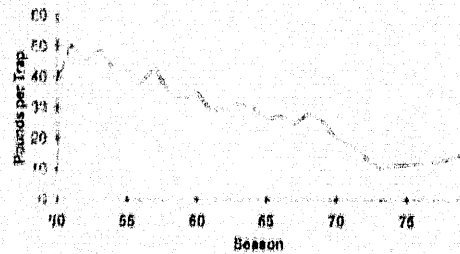
(a) Catch and effort

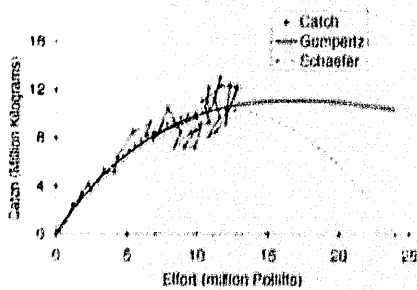**Figure 3.3 New Zealand Lobster**

(b) Catch per unit effort

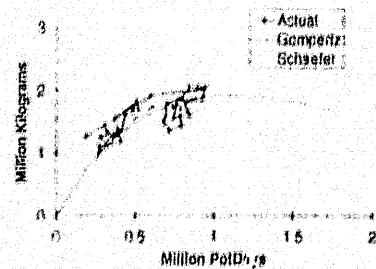Data: (Polacheck, Hilborn and Punt 1993)
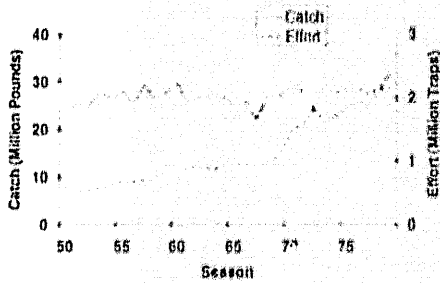
(a) Catch and effort
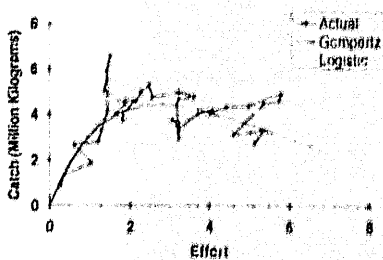
Figure 3.4 American Lobster

(b) Catch per unit effort

Data: (Townsend 1986)

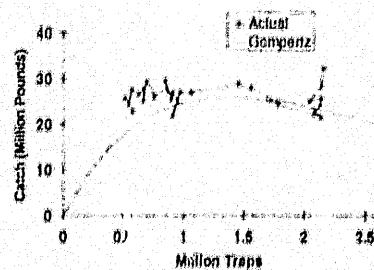(a) Western Rock Lobster

(b) Tasmanian Rock Lobster

(c) New Zealand Lobster

(d) American Lobster

Figure 3.5 Catch on effort for the four fisheries.

The scatter charts in figures 3.5a to 3.5d depict movements in the level of catch relative to effort. These graphs show yield plotted on effort, as in the production functions we are seeking. We have plotted some estimates of possible production functions on the graphs and these will be discussed in section 5.

4. Spatial and Temporal Distribution of Catch and Effort

We have shown in a recent paper, that changes in the distribution of effort over the season can introduce trends in annual CPUE. These trends are independent of changes in stock levels or harvest efficiency (Wallace, Lindner and Dole 1996b). This occurs because the catch per unit effort varies substantially between months in the season. If there is an increase in the proportion of effort allocated to months with low CPUE, then the annual CPUE (which is a weighted average of the CPUE by month) will fall, ceteris paribus.
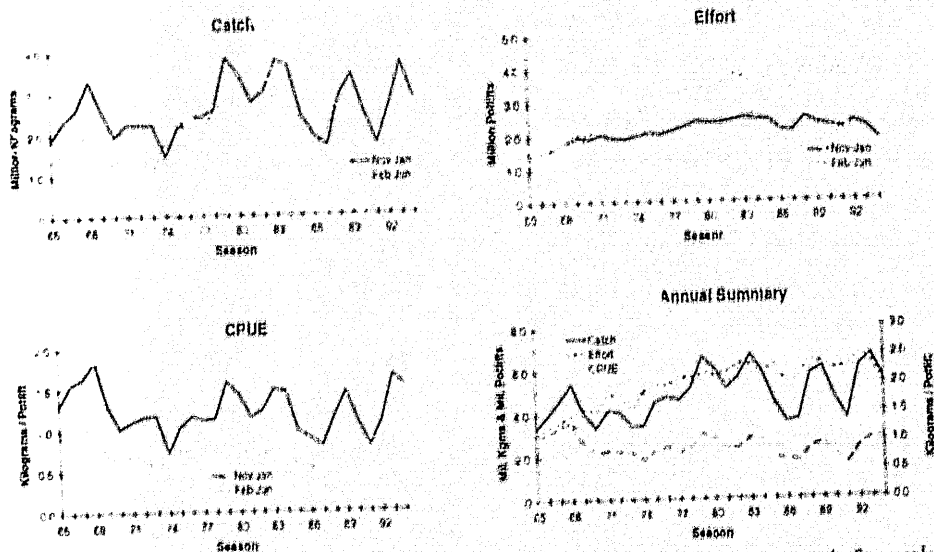

Figure 4.1 Western Rock Lobster Catch and Effort Statistics. Relative trends for early season (November to January) compared to the late season (February to June) for Catch, Effort and Catch per Unit Effort.

In the case of the Southern Zone of the Western Rock Lobster fishery, graphical analysis (Figure 4.1) shows that effort has increased for the months of February to June. CPUE is

very much lower during this period than it is between November and January. The CPUE has been higher, and more variable, during the early months of the seasons relative to CPUE in the later months, while showing no trend in each period. These characteristics of the data are more evident in graphs of the monthly data shown in Wallace, Lindner and Dole (1996b). The fourth graph in Figure 4.1 shows the annual data. This graph shows the small positive trend in effort, and the small negative trend in CPUE.

5 Results

5.1 Annual Analysis

Tables 5.1 and 5.2 show the results of linear regressions on Schaefer and Fox models for the four fisheries. The results are for ordinary least squares unless a Lagrange Multiplier test suggested significant residual serial correlation. If serial correlation was detected, the appropriate first or second order serial correlation was fitted using the exact AR Newton-Raphson iterative method. Viewed simplistically, the results appear satisfactory for all of the fisheries except the American Lobster. The coefficient values are comparable and accord with prior assumptions regarding signs and magnitudes, the F statistics support the existence of the models, and the t-statistics suggest that all coefficients are statistically significant. Furthermore, the resulting estimates of the sustainable yield functions appear to map the actual data well, as can be seen in the figures 3.5a to 3.5e. Recent catch and effort data are in close proximity to the estimated maximum sustainable yield, especially for the Gompertz model. The low R^2 values were anticipated because of the known impacts of environmental variability.

Table 5.1 Regression results for the standard Schaefer logistic model (equation 8) using all the available data. OLS or exact AR Newton-Raphson iterative method is used depending upon results of LM test for autoregressive processes.

Fishery		Western Rock Lobster	Tasmanian Rock Lobster	New Zealand Lobster	American Lobster
Method		AR(2)	OLS	AR(1)	OLS
Estimated	Int.	.732(.000)	.597(.020)	.337(.067)	-.031(.918)
coeff.s	R	-.424(.000)	-.134(.005)	-.080(.102)	-.000(.947)
(p values)	E	-.031(.000)	-.355(.087)	-.070(.037)	.015(.903)
Parameters	r	.732	.597	.337	-.031
of model	q	.031	.355	.070	-.015
	k	56.3	12.58	59.5	5420.4
Test	R^2	.334	.270	.279	.010
Statistics	$\overline{R}^2$	.274	.227	.226	-.066
	F-stat	5.53(.001)	6.29(.005)	5.28(.004)	.14(.873)
	d.o.f	4,44	2,34	3,41	2,26
	DW	1.90	2.29	2.03	1.81

Table 5.2 Regression results for the Fox Gompertz Model (equation 16) using all available data. OLS or exact AR Newton-Raphson iterative method used depending upon results of LM test for autoregressive processes.

Fishery		Western Rock Lobster	Tasmanian Rock Lobster	New Zealand Lobster	American Lobster
Method		OLS	OLS	AR(1)	OLS
Estimated	Int.	.258(.001)	.796(.021)	.327(.062)	.764(.486)
coeff.s	LnR	-.442(.000)	-.509(.008)	-.196(.098)	-.194(.457)
(p values)	E	-.026(.001)	-.466(.068)	-.087(.039)	-.142(.528)
Parameters	r	.442	.509	.196	.194
of model	q	.026	.466	.087	.142
	k	68.1	10.25	60.9	364.8
Test	R^2	.250	.251	.282	.031
Statistics	$\overline{R}^2$	.217	.206	.230	-.043
	F-stat	7.65(.001)	5.68(.007)	5.37(.003)	.42(.661)
	d.o.f.	2,46	2,34	3,41	2,26
	DW	1.63	2.17	2.05	1.62

In the case of the American lobster, both models perform very poorly. The coefficient estimates are not significantly different from zero according to t-tests, and in the case of

the Schaefer model the estimated coefficients are negative for both catchability and intrinsic growth rate. The results for the autoregressive Fox model in figure 4 are better, although the F-statistic is not significant even at the 90% confidence level. It was not possible to calculate a sustainable yield function from the logistic model, but figure 3.5d shows the Gompertz sustainable yield function.

We showed that the apparently good results for the first three fisheries in table 2 are illusory by repeating the regressions for shorter time intervals. In all cases, Chow test statistics for structural change (Harvey 1990) are significant for some point in the observed data. In the case of the Western Rock Lobster, this apparent structural change occurs in the late 1960's, shortly after the introduction of limited entry licensing in 1963/64. Chow tests applied to either the Schaefer or Fox models suggest that the break occurs from 1968/69. The Western Australian Department of Fisheries advise that effective enforcement of the limited entry regulations was achieved from about the 1968/69 season. The selection of the year for the structural break in the other fisheries was more arbitrary, and was based on visual analysis of the data and confirmed with Chow tests.

In all four fisheries, the estimate of the catchability coefficient is lower for the period after the structural break. For the Western Australian and Tasmanian fisheries, the estimated coefficient after the break is negative. This is confirmed by running separate regressions for the periods before and after the presumed break. Table 5.3 shows the results for the Western Rock Lobster, with auto-regressive processes estimated when significant. The regression results for the other three fisheries also resulted in much lower values for the catchability coefficient. See Wallace, Lindner and Dole (1996a) for details.

Table 5.3. Western Rock Lobster - Gompertz model results for selected time periods. OLS or exact AR Newton-Raphson iterative method used depending upon results of LM test for autoregressive processes.

Time Period		1945/6 -67/8	1968/9 - 93/4	1945/6 - 93/4
Method		OLS	AR(2)	OLS
Estimated	Intercept	.402 (.000)	-.275 (.068)	.258 (.001)
coefficients	LnR	-.682 (.000)	-.465 (.006)	-.442 (.000)
(p values)	E	-.038 (.001)	.021 (.117)	-.026 (.001)
Parameters	r	.682	.465	.442
of model	q	.038	-.021	.026
	k	47.4	-26.4	68.1
Test	R^2	.492	.590	.250
Statistics	R^2	.441	.512	.217
	F-stat	9.68 (.001)	7.55 (.001)	7.65 (.001)
	d.o.f.	2,20	4,21	2,46
	DW	2.03	1.84	1.63

An alternate view of this phenomenon is that the catchability coefficient is changing systematically over time. It is possible to identify a number of individual technological innovations that have increased efficiency in locating and harvesting the lobster stocks. Some innovations that have been introduced are Sonar, Global Positioning Satellite, improved hull designs, more effective pot designs, and engine improvements. Skippers have progressively taken up each of these innovations over several years. Furthermore, the accumulated knowledge gained from fishing experience and biological research has increased harvest efficiency. Therefore, the catchability coefficient should have increased over the observed time interval in all four fisheries. We can test this hypothesis by modifying the harvest equation to include a trend in catchability as in equation (20). The resulting structural equations, (21) for Schaefer and (22) for Fox, are highly complex.

$$(20) \quad H_t = q \cdot (1 + g \cdot T) \cdot E_t \cdot X_t$$

$$(21) \quad \frac{R_{t+1} - R_t}{R_t} = \frac{g}{1 + g \cdot T} + [1 + g \cdot T + g] \left[\frac{r}{1 + g \cdot T} - \frac{r}{q \cdot k \cdot (1 + g \cdot T)^2} \cdot R_t - q \cdot E_t \right]$$

$$(22) \quad \frac{R_{t+1} - R_t}{R_t} = \frac{g}{1 + g \cdot T} + [1 + g \cdot T + g] \cdot \left[\frac{r \cdot Ln\{q \cdot k \cdot (1 + g \cdot T)\}}{1 + g \cdot T} - \frac{r \cdot Ln\{R_t\}}{1 + g \cdot T} - q \cdot E_t \right]$$

Under our hypothesis that harvest efficiency increases over time, the additional parameter g in equations (21) and (22) should be positive. Table 5.4 shows that the non-linear least squares estimates for parameter g in equation (22) were negative for the Western Australian, Tasmanian, and American Lobster fisheries. The t-statistics for the q and k parameters for the Tasmanian fishery, and the Durbin-Watson statistic for the American fishery are poor.

Table 5.4 Fox Model Results of non-linear least squares estimation for equation (22).

Parameter	Western Rock Lobster	Tasmanian Rock Lobster	New Zealand Lobster	American Lobster
r	.64	.68 (.02)	.39 (01)	2.62 (.00)
q	.02	.28 (.38)	.16 (.05)	2.07 (.00)
k	69	17 (.32)	30 (.32)	41 (.00)
g	-.005	-.013 (.00)	-.013 (.00)	-.02 (.00)
R^2	.26	.34	.15	.32
R^2		.28		.24
F	N/A	5.6 (.00)	2.70 (.06)	3.88 (.02)
d.o.f.		3,33		3,25
DW		2.08		1.34

Estimation of the Schaefer model using equation (21) yielded results very similar to those for the Fox model. The estimates of the g parameter were negative for all of the fisheries.

The common feature of the above results is that the catchability coefficient has fallen over time in all four fisheries studied. While many of the individual results provide rather weak evidence independently, the combined weight of the evidence is strong. We have shown that catchability as defined in the surplus yield model has fallen over time in these fisheries.

5.2 Analysis of Monthly Data

In a recent unpublished paper, we showed that changes in the distribution of effort over the season can influence trends in annual CPUE (Wallace, Lindner and Dole 1996b). This effect occurs because annual CPUE is a weighted average of the CPUE by month, with the weights being the proportion of annual effort applied in that month. There are strong seasonal variations in catchability and stock levels. If the seasonal distribution of effort changes, then annual CPUE must also change, ceteris paribus. For the same reason, changes in the spatial distribution of effort will have similar effects. Figure 4 1 demonstrates these changes, and further evidence can be obtained from the regressions in the previous paper. The table in the appendix shows the results of the final regression from that paper. These demonstrate that monthly CPUE exhibits strong seasonal effects (the terms S_{Nov} to S_{Jun} are seasonal dummies). It also shows that the effect of new recruitment varies between different one degree geographical blocks. PSI_{t-3} and PSI_{t-4} are measures of recruitment derived from an index of settlement of the puerulus larvae. Because annual CPUE is a weighted average over both time and space for the season, its value will be changed by any changes in the temporal or spatial distribution of effort. The annual CPUE for different years are not directly comparable unless the temporal and spatial distributions of effort are identical for the different years.

6. Discussion

The apparent negative trend in catchability is the most significant outcome of this analysis. The evidence presented in section 5 strongly suggests that this has occurred in all four fisheries studied, and this is cause for concern for economists who use surplus yield production functions in bioeconomic models. In most industries, productive efficiency has increased markedly over time. For the reasons outlined in section 5, there is ample evidence to suggest that this is also the case in lobster fisheries. Therefore falling

catchability is an anomaly, and it is necessary to seek an explanation elsewhere for a solution. If we wish to continue to use surplus yield models in bioeconomic analysis, this matter assumes some considerable importance.

An additional finding is that the Gompertz model is preferred to the standard Schaefer model. First, the effort yield relationship takes a more realistic shape for species with high fecundity. Second, the empirical results perform better in diagnostic tests, especially in cases like the New Zealand and American fisheries where catches have declined over some portion of the time series.

Acknowledgments

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Regressions of *CPUE* by month in the Western Rock Lobster Fishery from 1972/73 to 1993/94, using an AR(1,2,3,8) process. (p values in brackets)

Regressor	Block 3014	Block 3115	Block 3215	Total South
S_{Nov}	.175 (.40)	.005 (.98)	.100 (.76)	.192 (.35)
S_{Dec}	.476 (.08)	.723 (.03)	-.775 (.12)	-.491 (.10)
S_{Jan}	.888 (.06)	.514 (.02)	.217 (.51)	.518 (.01)
S_{Feb}	.674 (.00)	.713 (.00)	.817 (.00)	.699 (.00)
S_{Mar}	.318 (.14)	.807 (.00)	.797 (.00)	.844 (.00)
S_{Apr}	.446 (.14)	.656 (.00)	.692 (.00)	.741 (.00)
S_{May}	.528 (.00)	.469 (.00)	.631 (.00)	.527 (.00)
S_{Jun}	.483 (.00)	.470 (.00)	.634 (.00)	.517 (.00)
$Ln(PSI_{t-1}) \times S_{Dec}$	.198 (.01)	.165 (.01)	.216 (.02)	.137 (.02)
$Ln(PSI_{t-3}) \times S_{Mar}$	.122 (.01)			
$Ln(PSI_{t-3}) \times S_{Apr}$	.089 (.06)			
$Ln(PSI_{t-4}) \times S_{Nov}$	.115 (.01)	.162 (.00)	.112 (.11)	.115 (.01)
$Ln(PSI_{t-4}) \times S_{Dec}$	.345 (.00)	.422 (.00)	.308 (.00)	.329 (.00)
$Ln(PSI_{t-4}) \times S_{Jan}$		.101 (.04)	.205 (.00)	.104 (.02)
R-bar^2	.878	.805	.730	.850
F-statistic	83.87 (.00)	46.85 (.00)	31.12 (.00)	64.17 (.00)
D-W	2.06	1.98	1.97	