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Fisheries Management with Stock Growth Uncertainty and Costly Capital Adjustment: Extended Appendix

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April 2005

Working Paper # 05011

Department of Economics Working Papers Series

Ames, Iowa 50011

Fisheries management with stock growth uncertainty and costly capital adjustment: Extended appendix

Section 1 of this Appendix describes the pacific halibut fishery and management program. Section 2 describes the data, functional specifications and the econometric methods used to calibrate the model.

1 The pacific halibut fishery

The pacific halibut (*hippoglossus stenolepis*) fishery extends through the Bering Sea and Gulf of Alaska along the North American pacific coast to California (see Figure 1). Large scale commercial development began in the 1880s with the completion of transcontinental railroads. Crutchfield and Zellner (1962) provide an extensive survey of the historical development of the fishery.

A 1923 convention between Canadian and U.S. Governments led to the establishment of the International Pacific Halibut Commission (IPHC). The IPHC consists of three government appointed commissioners for each country. The mandate of the IPHC is research and management of halibut throughout its northwestern North American range.

The Alaskan pacific halibut fishery, Management Units (MU's) 2C, 3 and 4, has operated under a system of individual fishing quotas (IFQs) since 1995 (Figure 1). The IFQ management program was adopted to address problems that accompanied a significant build up of the halibut fleet during the 1980's. Pre-IFQ managed program consisted of a total allowable catch limitation which was enforced with seasonal closures. Seasonal closures resulted in an inefficient *race for fish*, dangerous fishing conditions, excessive waste and bycatch among other problems (Committee to Review Individual Fishing Quotas, 1999; Pautzke and Oliver, 1997).

The IFQ system assigned quota shares to fishermen who made at least one halibut landing during the 1988, 1989 or 1990 seasons. The share allocated to qualifying fisherman was based on his or her largest catch recorded in five out of six years from 1985-1990. Individual landings records were then compared with total landings to determine the initial quota share.

Area specific quota share were allocated at no charge to 5,484 vessel owners. An important goal of the IFQ program designers, the North Pacific Fisheries Management Council, was to prevent dramatic restructuring of the halibut fishing fleet and to "maintain a diverse, owner-operated fleet" (Pautzke and Oliver, 1997). This objective was met by placing restrictions on the transferability of quota shares among halibut fishermen. No individual is permitted to own more that 0.5% of the total regional quota share. Quota shares are vessel class specific and only transfers from larger to smaller vessel classes are permitted. Some quota share categories may be owned only by fishermen with proven sea time, and these individuals are required to be on board the vessel when the quota

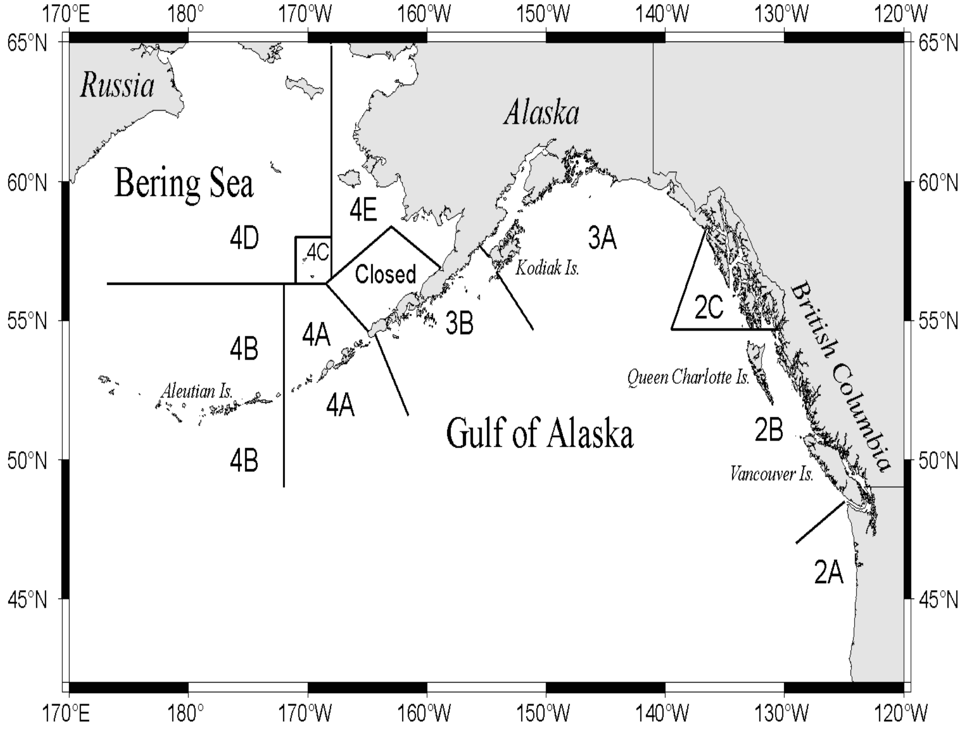

Figure 1: Management Units in the Pacific Halibut Fishery

is fished. Finally, a *blocking* system is used to control quota share consolidation.

If an initial quota share allocation resulted in less than 20,000 pounds of catch, based on the 1995 total allowable catch, the quota was issued as *blocked* quota. Quota share allocations less than 1,000 pounds may be swept up to form larger blocks. However persons are prevented from owning more than two blocks in each management unit. In effect, the blocking system imposes a cap on the total consolidation of quota that is legally allowed, and imposes a lower bound on the total number of vessels in the halibut fleet.

In order to gain perspective on the effects of the various transfer restrictions on fleet structure, note that the season length in the MU's 2C, 3A and 3B averaged 3.25, 3.83 and 4.29 days during the period used to determine the initial quota allocations (1985-1990). Season length restrictions are not required under the IFQ system and the halibut fishery now remains open for 245 days each year; from March 15 through November 15. The average initial quota that was allocated to the 5,484 recipients represents a small proportion of the quantity that could be harvested during a 245 day period. While considerable consolidation of the catch—onto fewer vessels—has occurred under the IFQ program, there is evidence indicating that most of the participating vessels continue to harvest small quantities of halibut each year.

Year	TAC	Total Vessels	Vessel Class	Active Vessels	Minimum harvest	Average harvest	Maximum harvest	25%-75% harvest
1995	33,625	2,166	1	749	< 0.1	4.1	246.7	[.6, 4.1]
			2	1225	< 0.1	15.0	174.1	[3.7, 18.2]
			3	192	1.0	63.2	221.0	[21.1, 94.6]
1996	36,726	2,103	1	800	< 0.1	4.7	61.3	[.7, 5.0]
			2	1128	< 0.1	18.3	186.6	[4.6, 22.0]
			3	175	1.1	70.3	229.5	[28.5, 102.9]
1997	51,199	2,131	1	895	< 0.1	6.4	204.6	[.8, 5.9]
			2	1077	< 0.1	26.1	264.7	[5.8, 31.1]
			3	159	0.7	109.0	420.9	[39.2, 164.0]
1998	53,550	1,780	1	690	< 0.1	8.5	234.6	[.7, 7.1]
			2	940	< 0.1	31.5	279.3	[7.3, 37.4]
			3	150	.7	120.5	442.1	[43.8, 188.4]
1999	59,046	1,802	1	708	< 0.1	9.7	219.0	[.8, 7.7]
			2	952	< 0.1	33.6	340.7	[7.1, 36.5]
			3	142	0.6	141.9	472.9	[58.1, 220.2]
2000	54,675	1,809	1	762	< 0.1	9.4	230.2	[.6, 6.9]
			2	919	< 0.1	31.3	372.0	[5.5, 33.5]
			3	128	.9	146.4	537.7	[57.2, 233.5]
2001	58,557	1,691	1	717	< 0.1	9.9	237.3	[.7, 7.5]
			2	846	< 0.1	37.8	341.9	[6.3, 40.2]
			3	128	.9	152.5	557.1	[64.7, 229.8]
2002	60,182	1,618	1	687	< 0.1	9.7	273.6	[.8, 8.2]
			2	805	< 0.1	42.4	338.8	[7.0, 46.4]
			3	126	4.6	153.9	551.5	[64.2, 250.2]

Table 1: **Annual Harvest, Fleet Size and Catch per Vessel, 1995-2002.** `Harvested quantity is in thousands of pounds.`

Table 1 reports the number of participating vessels, by vessel class, the minimum, mean, and maximum catch per vessel, and the 25% and 75% quantal catch per vessel during the first 8 years of the IFQ management program. The table shows that the number of vessels declined following the adoption of the IFQ management program in 1995. The downward trend in boats occurred even though the total allowable catch increased during the period, e.g., in 1997, the total allowable catch increased from 37,726 to 51,199 million pounds, 35.7%. Correspondingly, the average catch per boat exhibits a strong positive trend.

A striking feature of the data is the considerable variation in the catch per boat among participating vessels. For class 2 vessels, the average catch per boat in 1995 is less than 10% of the maximum catch recorded. Twenty-five percent or 306 class 2 vessels harvested less than 2% of the largest catch reported. In 2002, the average catch per boat is 12.5% of the maximum reported catch and 25% of vessels, roughly 404 boats, harvested less than 2% of the maximum reported catch. A similar pattern is indicated for other vessel classes and in other years.

The catch statistics in Table 1 confirm that most of the active vessels in the halibut fleet continued to harvest small quantities during the first 8 years of the IFQ program, and considerable further consolidation of the catch onto fewer vessels is possible. Vessel participation and catch data in the fishery clearly demonstrates the effects of the transferability restrictions imposed under the IFQ program. Most vessels face a binding constraint on the quantity that is harvested each year.

2 Empirical Calibration of the Model

This section describes the data and the estimation methods used to calibrate the following components: (1) the halibut stock growth function, (2) the harvest benefit function, (3) the fleet harvesting cost function, and (4) vessel capital adjustment costs.

2.1 Data

We collected data from the following sources: a survey of halibut fishing costs conducted by the Institute of Social and Economic Research at the University of Alaska; landings data from the National Marine Fisheries Service, Restricted Access Management Division; stock abundance data maintained by the IPHC. These data were supplemented with information gathered from halibut fishermen (vessel owner/operators), other industry sources and the IPHC.

The harvest cost data are available for Alaskan fishermen operating in MU's 2C, 3 and to a lesser extent MU 4 (see Knapp 1999 for a complete discussion of the data). We were unable to obtain vessel cost data from the Canadian fleet, which operates in MU 2B. While Canadian boats use similar capture techniques, extrapolation of the US fleet cost is problematic. This is because the average distance between the vessel's port and halibut fishing grounds, an important factor in variable harvesting costs, is likely to vary across regions. Extrapolating US-based harvest costs to the Canadian fleet could bias the results.

Knowledge of the stock characteristics for the halibut resource also varies across MU's; e.g., stock abundance data for MU 3B and 4 is unavailable. For these reasons, the analysis will focus on MU 3A. This MU produces roughly 55% of all commercial harvests (U.S. and Canada), is well-represented in our 1997 harvesting cost data, and has the most complete stock abundance information within the U.S. segment of the fishery.

Data used to estimate the vessel harvest cost function is from a survey of Alaska halibut vessel owners and operators who fished for halibut during the 1997 harvest season. The data contain detailed information on harvest quantity, fixed and variable operating expenses, vessel and crew sizes, vessel resale values, and other socioeconomic information. Complete information for 102 vessel observations are available with 24 class 1 vessels (less than 35 feet in length), 69 class 2 vessels (greater than 35 feet and less than 60 feet in length), and 9 class 3 vessels (exceeding 60 feet in length).

Vessel refit costs, i.e., the costs incurred to ready a vessel to switch from the halibut fishery to some other fishery, or visa versa, are not included in the cost survey. We consulted halibut skippers to obtain estimates of refitting costs, and the number of trips that could be made in a season in the absence of quota constraints.

Nine halibut captains were queried regarding: (1) vessel hold capacities and icing systems; (2) crew sizes; (3) the number of trips that could be taken if unconstrained by quota, under varying levels of stock abundance; (4) new vessel purchase prices; (5) old vessel scrap values and; (6) vessel refitting activities and expenditures. While a larger sample would have been preferred, responses were consistent across interviewees.

Halibut skippers indicated that vessel refit costs depend largely on which fisheries the vessel is moved between. If a vessel is moved from a fixed gear fishery (into the halibut fishery), refit costs are considerably less than if the vessel is moved from a trawl gear fishery. Modeling the set of fisheries in which vessels participate is beyond the scope of this study. Hence, the survey information on refitting costs is used to generate plausible ranges for refit costs rather than precise estimates.

2.2 Halibut stock dynamics

The IPHC has developed a region and sex specific, age structured model of halibut stock abundance. The model tracks the number of fish and average weight at age, by region, sex and age. Survival, growth and recruitment of young fish into the commercially exploitable population is tracked over time. Factors affecting changes in abundance such as harvest selectivity (the likelihood that longline gear will intercept halibut of a given size and age), fecundity at age, recruitment of young into the commercial fishery, among other factors are incorporated into the model (see Sullivan, Parma, and Clark, 1999). In each year new commercial data and in some years survey data are collected. These data are used in a Bayesian framework to update estimates of the exploitable biomass.

Value function iteration computation time increases exponentially with the number of state variables. Adopting the IPHC stock model directly increases the number of state variables to well over 50 and thus is not practical. Our approach is to fit a parsimonious parametric model to characterize the growth of the exploitable halibut biomass. For this purpose we aggregate across age classes and sex to obtain the measure of the pre-harvest exploitable biomass, x_t, the catch, h_t, and the escapement, s_t, by management unit and year. The data are available for management units 2B and 3A from 1974 through 2003.

Growth of the halibut exploitable biomass is comprised of two components. The escapement of adult halibut from the previous harvest season feed and grow, and some adult fish die from natural causes. The growth of the adult escapement is density dependent since fish must complete for a finite food supply. The second component of total stock growth comes from the new recruits that enter the exploitable biomass. The regulatory program in the halibut fishery imposes a minimum 81 centimeter length limit on the commercial catch. New recruits into the fishery consists of roughly 6-7 year old female fish (who grow faster than males) and 8 year old male fish.

Spawning female pacific halibut produce larvae which are broadly dispersed by ocean currents. Fisheries scientists at the IPHC consider the ocean environmental conditions, in particular water temperatures which are influenced by global weather patterns, to be an important determinant of the survival of halibut larvae (Clark and Hare, 2002). Ocean weather patterns tend to be cyclical. These factors suggest that the random shocks to the halibut stock growth, z_t in period t, will be serially correlated over time.

Assume the exploitable biomass follows a Markov process $\{x_t\}$ with transitions governed by

$$x_{t+1} = z_{t+1} G(s_{t+1}), \tag{A.1}$$

where $G(s_{t+1})$ is deterministic growth given escapement, s_{t+1}. The multiplicative shock z_{t+1} is strictly positive with mean 1 and finite support $[\underline{z}, \overline{z}]$, where $0 < \underline{z} < \overline{z} < \infty$.

Estimation requires a functional form for the deterministic growth component $G(.)$. The logistic stock growth model and the Ricker models are selected. The random shock process is approximated by the following estimation equation:

$$z_{t+1} = \varsigma + \rho z_t + \varepsilon_{t+1} \tag{1}$$

with $\varsigma + \rho = 1$, and ε_{t+1} is a mean zero error term with finite variance, σ_ε^2. When $\rho \neq 0$ the process exhibits first order serial correlation, whereas $\rho = 0$ indicates independent and identically distributed shocks.

Feasible generalized non-linear least squares is used to estimate the model parameters. An iterative procedure is used to minimize[1]

$$v' \sum^{-1} v$$

where v is a $(T-1)$ vector of data with t'th element

$$v_t = [x_{t+1}/G(s_{t+1})] - 1,$$

and $\sum$ is a variance-covariance matrix with the following structure:

$$\sum = \frac{\sigma_\varepsilon^2}{1-\rho^2} \begin{bmatrix} 1 & \rho & \dots & \rho^{T-1} \\ \rho & 1 & \dots & \rho^{T-2} \\ \vdots & \vdots & \ddots & \vdots \\ \rho^{T-1} & \rho^{T-2} & \dots & 1 \end{bmatrix}.$$

The Logistic growth model is given as $G(s_t) = s_t + \gamma s_t(1 - s_t/x^c)$, and the Ricker model takes the form $G(s_t) = s_t + \theta_1 s_t \exp(-\theta_2 s_t)$. The iterative procedure used to estimate the parameters of each model stabilized after 3 iterations. The growth functions provided indistinguishable fits to the stock data. The Logistic model is chosen for the analysis. It should be emphasized that the *true* growth model for the pacific halibut stock is not known, and there is no way to assess if either the Logistic or Ricker specifications provide a good fit to true growth. This is because the stock abundance data is itself generated from a model.

For completeness, and with the above caveat regarding the nature of the stock data in mind, a bootstrap procedure is used to calculate 90% confidence intervals for the parameters of the logistic growth model and serially correlated shock process. Parameter estimates[2] and 90% confidence intervals are reported in Table 2.

Figure 2 shows the 1974-2003 stock data, the fitted Logistic growth model and 99.9% confidence intervals for the multiplicative shock.

The state space for the random shock z_t and the Markov transition matrix are calculated following Judd (1998, p. 85-88). Lower and upper bounds, $\underline{z}$, and $\overline{z}$, are chosen to encompass 99.9% of the (empirically estimated) shocks that occurred during 1974-2003.

Specifically, the estimated shock in period $t+1$ is $\widehat{z}_{t+1} = x_{t+1}/\widehat{G}(s_{t+1})$ where $\widehat{G}(.)$ denotes the fitted Logistic growth function. We first divide the state spate into n^z intervals of width $\Delta = \frac{\overline{z}-\underline{z}}{n^z}$.

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[1] Preliminary data analysis revealed that the recruitment was extremely large in 1989, 1993 and 1994. A dummy varaible for these unusual years was added to model to obtain more representative estimates of α_1, and α_2. The unusually high recruitment in 1989, 1993 and 1994, is factored into the estimate of σ_ε^2.

[2] The parameter estimates for the Ricker model are $\gamma_1 = 1.285$, and $\gamma_2 = 0.054$.

Parameter	Estimate	90% C.I.
γ	0.283	[0.240, 0.339]
x^c	443,392.070	[392,670.808, 570,851.660]
ζ	0.635	[0.416, 0.907]
ρ	0.365	[0.101, 0.593]
σ_ε	0.041	[0.035, 0.050]

Table 2: Growth Model Parameter Estimates (Logistic Growth Model)

Interval j is then given by $[\underline{z} + (j-1)\Delta,\ \underline{z} + j\Delta]$. Let z_j denote the midpoint of interval j; $z_j = \underline{z} + (j - \frac{1}{2})\Delta$. We calculate the probability that, conditional on the current state $z_t = z_j$, the one period ahead shock $z_{t+1} = z_i$ for all $i = 1, .., n^z$. This probability is calculated as

$$(2) \qquad P(i,j) = \Pr(z_{t+1} = z_i | z_t = z_j) = \Pr(z_i - .5\Delta \leq \zeta + \rho z_j + \varepsilon \leq z_i + .5\Delta).$$

In words, $P(i,j)$ is the probability that period $t+1$ shock takes the value z_i given $z_t = z_j$.

The estimated transition probabilities are shown in Figure 3. The results illustrate positive serial correlation between subsequent period shocks reflecting decadal changes in environmental conditions that influence halibut stock growth rates (see Clark, et al., 1999).

2.3 Harvest benefit function

Criddle and Herrmann (2003) develop and estimate a comprehensive model of the pacific halibut market. The model considers prices in the U.S. wholesale market, prices in the U.S. and Canadian ex-vessel markets, U.S. inventories, halibut imports from British Columbia, and the linkage between the import and the wholesale prices. Criddle and Herrmann estimate that the own-price flexibility (for the period 1976-2002) in the U.S. wholesale market is -0.29.

Under the assumption that all markets are competitive, the wholesale demand for halibut in the U.S., which is the primary market for pacific halibut, is used to calculate the total benefit function, $B(.)$. We adjust the linear demand equation estimated in Criddle and Herrmann to approximate the residual demand and corresponding benefit function for halibut production from MU 3A. Our simplifying assumption is that the MU 3A harvest can be treated independently from the rest of the fishery. The residual inverse demand function is obtained as the solution to

$$P_{1997} = \alpha_1 - \alpha_2 h_{1997},$$

where P_{1997} is the 1997 annual average ex-vessel price and h_{1997} is the total harvest in management unit 3A in 1997. The estimate if the parameter α_2 is 0.000036. $P_{1997} = \$2.17$, and $h_{1997} = 22,650$ thousand pounds which implies $\alpha_1 = 2.9854$.

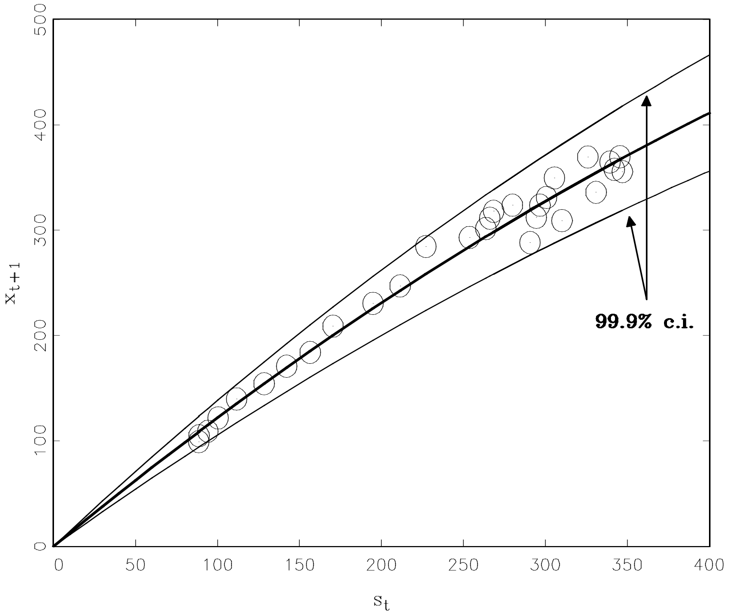

Figure 2: Stock Growth Function (Management Unit 3A)

Integrating under the demand curve yields the period t benefit of harvest h_t, i.e., the sum of consumer surplus and industry revenues:

$$B(h_t) = \alpha_1 h_t - \frac{1}{2}\alpha_2 h_t^2,$$

where h_t indicates thousands of harvested pounds, and $B(h_t)$ denotes thousands of 1997 dollars.

2.4 Harvesting costs

Halibut fishing involves steaming from port to a chosen fishing site where a heavy long line is lowered to the sea bottom. Smaller lines with baited hooks are attached to the long line usually at 18 foot intervals. The long line is soaked and later recovered using a hydraulic winch. Hooked fish are retrieved, eviscerated and placed on ice. The catch is then returned to port and sold primarily to fish brokers who distribute the halibut primarily in fresh form to retail markets and restaurants. The analysis assumes a halibut fleet that is comprised of class 2 boats. For completeness, we report results of the harvest cost estimation all three vessel classes.

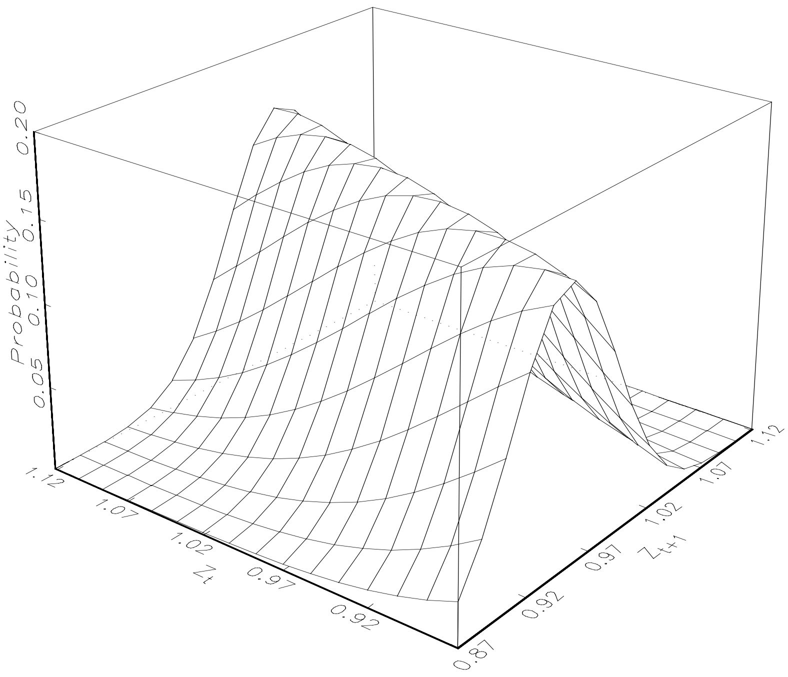

Figure 3: Transition Probabilities for Multiplicative Shocks

2.4.1 Variable costs

Variable operating expenses include expenditures on fuel, bait and ice, and food and supplies for the captain and crew, and occasional expenses to replace lost gear. The severe restrictions imposed on quota share consolidation under the IFQ management program suggest that it is reasonable to assume catch (output) is pre-determined and that vessel captains choose variable inputs to minimize the cost of harvesting their quota allocation. A dual minimum cost function will be specified for empirical estimation of the harvest technology.

The nature of commercial fishing suggests variable harvesting costs increase, possibly sharply, as harvest quantity approaches a maximum or peak capacity level for a fishing vessel operation. The vessel is an essential input in the harvesting process, and due to space limitations, vessels of fixed size can accommodate a limited crew. The productive services from a vessel of fixed length operated during a given harvest season are thus constrained, which implies that diminishing returns to the vessel capital must occur at large harvest quantities. We assume variable costs can be approximated by a cubic function of harvest quantity. For example, the harvest cost surface may be fairly flat over a wide range of output levels, but rise sharply as output reaches the physical capacity of a vessel. The cubic functional form is flexible and capable of representing a range of hypothesized cost surfaces.

Dropping time subscripts to ease notation, variable operating costs for vessel class $\kappa = 1, 2, 3$ are,

$$vc^{\kappa} = \beta_0^{\kappa} + \sum_m \beta_m d_m + \beta_1^{\kappa} q + \beta_2^{\kappa} q^2 + \beta_3^{\kappa} q^3 + \epsilon, \tag{3}$$

where d_m is a dummy variable for MU, m = 2C, 3A, 3B, and 4, q is quantity harvested, and ϵ is a disturbance term assumed to have zero mean and finite variance. Regional dummy variables control for cost variation due to regional differences in steaming times from port to a vessel's preferred fishing ground, as well as unobserved differences in stock abundance.

Ideally the data would contain observations on small, moderate and large, i.e., near physical capacity, harvest quantities. A wide range of observed output levels could identify the entire variable cost surface. Due to restrictions on halibut quota transfers, however, most vessels in our data harvested small quantities of halibut in 1997. Halibut skippers indicate that a class 2 boat that is unrestricted by halibut quota, with a good crew and average halibut stock abundance, is capable of harvesting roughly 1,315,000 pounds during an 8 month fishing season. The 69 class 2 sample vessels in our data harvested on average 24,804 pounds per boat (with a range of 803 to 125,000 pounds).[3] The average catch of the 1997 sample vessels is less than 2% of the maximum feasible output reported to us by halibut vessel skippers. The 1997 data are unable to characterize the shape of the harvest cost function over the full range of feasible output levels.

To compensate for this data limitation, we estimate the variable cost model in equation (3) adding the following restriction for vessel class κ,

$$\left.\frac{\partial vc^{\kappa}}{\partial q}\right|_{q=\widehat{q}} = \beta_1^{\kappa} + 2\beta_2^{\kappa}\widehat{q} + 3\beta_3^{\kappa}\widehat{q}^2 = \widehat{mc} \tag{4}$$

Equation 4 equates the marginal harvesting cost, evaluated at quantity $\widehat{q}$ to $\widehat{mc}$. For each vessel class we set the quantity $\widehat{q}$ equal to the maximum feasible harvest quantity reported to us by halibut skippers.

The restriction in 4 *forces* the marginal harvesting cost to rise to the value $\widehat{mc}$ when the harvest

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[3] Similarly, the same fishermen report that a class 1 boat is capable of harvesting over 326,000 pounds of halibut during an 8 month season. The average 1997 catch for the 24 class 1 vessels in our sample is only 6,804 pounds with a range of 215 and 30,000 pounds. Lastly, class three boats are capable of harvesting roughly 2,315,000 pounds during an 8 month season; the 9 class 3 boats in our data averaged a mere 81,746 pounds per boat, with range of 15,000 and 280,000 pounds.

Para.	Estimate	Std. Error
β_0^1	-0.727	1.711
β_1^1	0.125	0.347
β_2^1	0.413e-2	0.015
β_3^1	0.574e-6	0.287e-4
β_0^2	-0.661	1.459
β_1^2	0.129	0.060**
β_2^2	-0.387e-3	0.571e-3
β_3^2	0.749e-6	0.279e-6**
β_1^3	-4.830	3.702*
β_2^3	0.396	0.077**
β_3^3	0.285e-6	0.720e-7**
β_{2C}	0.997	1.160
β_{3A}	1.114	1.157
β_{3B}	0.526	1.743

Table 3: Vessel Cost Function Parameter Estimates. `Single (double) asterisk denotes parameter is significant at the 95 % (99 %) level.`

quantity reaches $\widehat{q}$ thus ensuring that the fitted variable cost function is strictly convex. We are unaware of any theoretical guidance which would help us in selecting $\widehat{mc}$. We thus rely on the feedback provided by halibut skippers, and information available on quota leasing activity. Our approach is to set $\widehat{mc}$ to a value that provides a good fit to the available cost data, and conforms strictly to the information provided to us by halibut fishermen. Table 3 reports parameter estimates and standard errors under the assumption that $\widehat{mc} = \$3$.

A second limitation we encounter is that because the data is for 1997 only, there is no variation in stock abundance, and consequently no way to identify *stock effects*, i.e., the cost effect due to changes in stock abundance. Grafton, Squires and Fox (2000) estimate a harvest production function using an incomplete panel of vessels that fished for halibut in Canadian waters during the 1988, 1991 and 1994 seasons. The authors report an elasticity of output with respect to halibut biomass equal to 1.0281 (the estimate is significant at the 5% level). Exploiting the dual relationship between the harvest and cost function we assume the same stock affect is present in the Alaskan halibut fishery. More precisely we assume that a one-percent increases in the stock abundance reduces the variable harvesting costs by 1.0281%.

Notice that the variable harvest costs that are estimated from our 1997 sample of Alaskan halibut fishermen are conditional on the stock abundance in that year, which from the IPHC data was relatively high compared to the 1974-2003 average. This means that the fitted variable costs as represented in Table 3 will underestimate the costs in an *average* stock abundance years. We assume the following functional form,

$$vc^{\kappa} \cdot \phi(x) = \left(\widehat{\beta}_0^{\kappa} + \sum_m \widehat{\beta}_m d_m + \widehat{\beta}_1^{\kappa} q + \widehat{\beta}_2^{\kappa} q^2 + \widehat{\beta}_3^{\kappa} q^3 \right) \left(\frac{x}{x_{97}} \right)^{-\beta_x}, \tag{5}$$

where 'hats' denote estimated parameter values, x_{97} is stock abundance in 1997 and $\beta_x = 1.0281$[4] Notice that if stock abundance, x, is equal to the 1997 value, variable harvesting costs are $\widehat{\beta}_0^{\kappa} + \sum_m \widehat{\beta}_m d_m + \widehat{\beta}_1^{\kappa} q + \widehat{\beta}_2^{\kappa} q^2 + \widehat{\beta}_3^{\kappa} q^3$ as required.

2.4.2 Annual fixed costs

Annual fixed costs include expenses for vessel mooring and storage, permits and licence fees, and fees for accountants, lawyers, and office support. Fishing vessels also require routine maintenance and repairs, periodic haul out for more extensive hull maintenance and occasionally, major repairs. Maintenance and repair costs will vary with vessel use but for simplicity are included as a fixed operating cost. Annual fixed costs by vessel size class are estimated at \$8,143 for class 1 vessels, \$21,100 for class 2 vessels, and \$54,050 for class 3 vessels.

Many vessels in the Alaskan halibut fishery spend only a portion of the year fishing for halibut. These vessels regularly participate in other fisheries to utilize otherwise idle vessel capital services. The cost of refitting a vessel to harvest with longline gear, will depend on the fishery from which the vessel is converted. Halibut fishermen inform us that the cost of refitting a boat which already uses fixed gear requires a relatively modest refit at a cost of approximately \$7,650, \$27,000, and \$45,000, respectively for a class 1, 2 and 3 boat.[5] If the boat is switched from a trawl gear fishery, the refit costs increase to \$20,000, \$85,000 and \$150,000, respectively, per class 1, 2 or class 3 boat. It should be noted that these refit cost estimates do not include human capital adjustment costs for example, the costs to retrain the captain and crew to fish for a different species, using different gear.

The cost of labor services of the captain and crew remains. While labor is often treated as a variable input, crew services are not easily adjusted in the short run. Fishing vessels are designed to accommodate a specific crew size. The crew may be increased or decreased by one or possibly two members but crew size adjustments tend to be infrequent. As in most fisheries, crew remuneration in the halibut fishery follows a revenue share system. Shares vary considerably depending on responsibilities and experience of the crew member.

Labor inputs are assumed to be used in fixed proportion to vessel capital. The value of labor is

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[4] We thank an anonymous referee for suggesting this specification. An additive linear specification for the stock effect, where the constant term in equation 3 took the form $\widehat{\beta}_0^{\kappa} = \widehat{\beta}_0^{\kappa} + \beta_x x$ for vessel class $\kappa = 1, 2, 3$, yielded qualitatively similar results.

[5] These are the mean responses reported by halibut skippers.

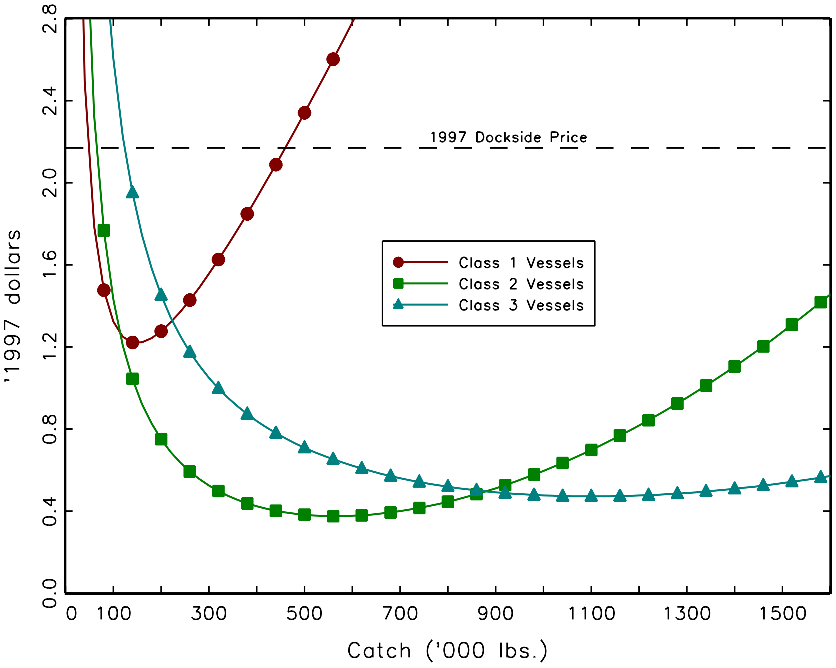

Figure 4: Vessel-level Average Harvest Costs

assumed equal to its opportunity cost which we take as the 1997 annual average salary of fishing and forest industry employees in the state of Alaska (Bureau of Labor Statistics, 1997). Average crew size (including the captain) for class 1 vessels is 2.23 implying seasonal labor cost of $87,166, at $39,088 per crew member. Average crew size for class 2 and class 3 vessels is 2.90 and 4.63, respectively, implying seasonal labor costs of $113,355 for class 2 vessels and $180,977 for class 3 vessels.

Fitted average cost functions evaluated at 1997 stock abundance (Management Unit 3A) are shown in Figure **??**. The results suggest that class 2 vessels attain minimum average cost of $0.38 per pound at harvest quantity of 560,000 pounds per season. While minimum average cost is predicted to occur at a harvest level that far exceeds the sample average (24,804 pounds), it is also well below the maximum feasible quantity of 1,315,000 pounds reported by halibut skippers. Figure **??** shows that under 1997 stock conditions, minimum average cost for class 1 vessels is $1.22 per pound at a harvest quantity of 140,000 pounds per season. This quantity exceeds the sample average harvest of 6,804 but is also below the maximum feasible quantity of 326,000 pounds reported by halibut captains. Similarly, for class 3 boats minimum average cost is $0.47 per pound at 1,100,000 pounds per season.

The average ex-vessel price for halibut in 1997 was $2.17 per pound suggesting considerable resource rents were available in the fishery, if vessels exploit all available returns to scale. Our estimates suggest per pound rents in the range of \$0.95, \$1.81, and \$1.70 for class 1, 2 and 3 vessels, respectively. Interestingly, records of quota leasing in the fishery by class 1 boats in 1997 indicate an average lease price of \$0.92 per pound. Our cost estimate results appear consistent with leasing activity in 1997. The lease price data did not allow a similar assessment of larger vessel classes.

The estimated variable harvest costs are combined with estimates of fixed costs, FC, and stock effects to obtain an estimate of vessel-level cost function, $c(q, x) = FC + vc^{\kappa}\phi(x)$. Assuming that the halibut fleet is comprised of class 2 boats, fleet harvesting costs are then given as $C(h, k, x) = k \cdot c(q, x)$, where k is the number of boats, $q = h/k$ is total harvest divided equally among active vessels, and $c(q, x)$ is individual vessel harvest costs (class 2 boats).

2.5 Capital adjustment costs

The capital price is specified as:

$$p_k = \begin{cases} p_k^+, & \text{if } k_{t+1} > (1-\delta)k_t \\ p_k^-, & \text{if } k_{t+1} \leq (1-\delta)k_t \end{cases},$$

where δ denotes physical capital depreciation. The cost of adding an additional boat to a fishing fleet may be as high as the price of a new boat, which our survey of vessel captains suggests is roughly \$800,000. The revenue generated by selling off a unit of capital could be as low a zero if, for example, a vessel has no alternative uses. More generally, the price of vessel capital depends on its value in a next best alternative use. The next highest-valued use for a commercial fishing vessel is likely to be in another fishery, ideally one which utilizes similar gear. The pacific halibut fishery is one of many in North America alone, and industry magazines provide evidence of a well-functioning vessel resale market. The price at which a vessel can be sold is set equal to the median self-reported vessel resale value obtained from the cost survey data; $p_k^- = \$160,000$. We set the cost of adding a new vessel to the resale price plus the costs of refitting the vessel to fish for halibut. We use the mid-level refit costs reported in our survey of halibut fishermen. In the baseline calibration $p_k^+ = \$236,500$. The cost survey data includes a self-reported measure of capital depreciation. The sample average value is 0.1.

Table 4 summarizes the calibration results. Harvest cost estimates for class 2 boats are reported.

Model Component	**Functional form**	**Base Case Parameters**
Deterministic stock growth	$G(s_t) = s_t + \gamma s_t(1 - s_t/x^c)$	$\gamma = 0.283,\ x^c = 443,392.07$
Multiplicative shock	$z_{t+1} = \varsigma + \rho z_t + \varepsilon_{t+1}$	$\varsigma = 0.635$; $\rho = 0.365$; $\sigma_\varepsilon^2 = 0.413e^{-1}$
Harvest benefit	$B(q_t) = \alpha_1 q_t - \frac{1}{2}\alpha_2 q_t^2$	$\alpha_1 = 2.9854$; $\alpha_2 = 3.6e^{-4}$
Fleet harvest cost Vessel cost (class 2 boats)	$C(h_t, k_t, x_t) = k_t \cdot c(q_t, x_t)$, $q_t = h_t/k_t$, $c(q_t, x_t) = FC + \left(\sum_{j=0}^{3} \beta_j q_t^j\right)\left(\frac{x_t}{x97}\right)^{-\beta_x}$	$FC = 134.451$; $\beta_0 = 0.453$; $\beta_1 = 0.130$; $\beta_2 = -0.387e^{-3}$; $\beta_3 = 0.750e^{-6}$; $\beta_x = 1.0281$; $x_{97} = 347,044$
Capital price	$p_k = \begin{cases} p_k^+, & \text{if } k_{t+1} > (1-\delta)k_t \\ p_k^-, & \text{if } k_{t+1} \leq (1-\delta)k_t \end{cases}$	$p_k^+ = \$236,500$; $p_k^- = \$160,000$; $\delta = 0.1$

Table 4: Model Calibration Summary.

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