Optimal fisheries management with stock uncertainty and costly capital adjustment

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Abstract

We develop a model of a fishery which simultaneously incorporates random stock growth and costly capital adjustment and use numerical techniques to solve for the corresponding optimal fishery management policy. The model identifies the resource rent maximizing harvest and capital investment policies under realistic conditions, and allows us to assess the bioeconomic performance of actual fisheries management programs. We apply the model to the Alaskan pacific halibut fishery. Our results show that departures from the optimal harvest policy have a negligible effect on the value of the halibut fishery, but regulations affecting private investment in fishing capital reduce the value of the fishery by as much as 40%. These results inform ongoing debates over the underlying causes of management problems in U.S. fisheries.

Key Words: Random stock growth, capital adjustment, fishery management, pacific halibut fishery.

JEL Classification: Q2, D2

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1 Introduction

Fisheries management in the United States has recently received sharp criticism for failing to manage biological resources to meet conservation goals and for failing to protect fishing communities whose livelihoods depends on healthy fisheries resources. Some critics allege that harvest rates are set above sustainable levels, citing pressure from industry as the source of the problem (U.S. Commission on Ocean Policy, 2004; Eagle, Newkirk, and Thompson Jr., 2003). One suggested recommendation is to decouple management decisions, with fisheries scientists determining harvest levels and industry allocating the harvest among user groups. Other critics cite oversized fishing fleets as the primary cause of management failure (FAO, 1999; Munro, 1998; Federal Fisheries Investment Task Force, 1999; see also NMFS, 2003). Expensive vessel buyback programs are currently underway in several U.S. fisheries.[1]

These recent criticisms of U.S. fisheries management policy have focussed on biological or economic aspects in isolation. In practice, fisheries managers must balance biological, economic and social goals under uncertain environmental conditions. The complexity involved in building and solving stochastic, dynamic models of fisheries has prevented the development of an analytical framework that encompasses key management trade-offs. In the absence of such a framework, critics and managers alike are unable to pinpoint the sources and magnitudes of management failures and identify promising directions for policy change.

In this paper we address this problem by building and solving a dynamic model of fishery management incorporating two fundamental features of real world fisheries: uncertainty

[1]The cost of removing excess capacity from five federally managed fisheries alone, is estimated to be $1 billion (NMFS, 2002).

regarding the growth of the biomass and capital adjustment costs. While it has long been recognized that stock growth uncertainty and costly capital adjustment are important elements of the fisheries management problem (Pindyck, 1984), much of the literature to date has focused on these components in isolation.[2] Reed (1979) shows that if harvest benefits are *linear* in the catch, the value of a stochastically growing fish stock is maximized under a constant escapement policy. The optimality of constant escapement policy depends critically on the assumption of constant marginal net benefits from the catch. With costly capital adjustment, and diminishing returns to fishing capital, the marginal net benefits from harvesting fish diminish as the current period harvest is increased.[3] Diminishing returns from current harvest creates an incentive to smooth the catch over time which has been largely overlooked in the literature. Previous studies that have attempted to incorporate capital adjustment constraints and stochastic stock growth been forced (by computational difficulties) to rely on ad hoc assumptions regarding stock dynamics, and/or the investment behavior of fishermen (see Charles, 1983, 1985).

This paper uses Value Function Iteration techniques to solve a dynamic model of optimal fishery management under stock uncertainty and costly capital adjustment. We derive optimal harvest and capital investment policies under conditions faced in real world fisheries. In stark contrast to the constant escapement policy, the optimal annual harvest in our environment varies only moderately over time, even though this necessitates a reduction

[2] See Smith, 1968, 1969; Clark, Clarke and Munro, 1979; Reed, 1979; Berck and Perloff, 1984; Boyce, 1995.

[3] There are two reasons to expect diminishing returns to the current harvest. Consumer demand may be inelastic causing marginal consumer benefits to decline as the per period harvest quantity rises. Second, diminishing marginal productivity of the current capital stock causes short run marginal costs of harvesting fish to increase as harvest increases.

in the average rate of stock growth. Furthermore, the optimal harvest is a function of the fleet size, since the immediate harvest value of the resource is greater when there are more boats available to catch fish. As one might expect, an increase in capital adjustment costs leads to a reduction in harvest variability; when it is more costly to move boats in and out of the fishery, it is better to reduce the variability of the harvest even though this will reduce expected yields over time.

Our model and solution method fill a gap in the fisheries management literature and importantly, provide a benchmark from which actual fisheries management programs can be assessed. We use the model to assess the bioeconomic performance of the management program currently in place in the Alaskan pacific halibut fishery. We first characterize the optimal—resource rent maximizing—management policy in the halibut fishery, and then quantify the costs, in terms of reductions in the present value of the halibut fishery, caused by departures from the optimal policy. We characterize the actual management regime as departing from the optimal policy along the following dimensions. First, the halibut fishery is managed using a constant harvest rate rule, whereby the yearly harvest is set to a fixed proportion, 20%, of the exploitable biomass. Second, the fishery is overcapitalized. The pacific halibut fishery was managed without entry restrictions for much of its history. This lead to a build up of capital common in open access settings (Crutchfield and Zellner, 1962, and Pautzke and Oliver, 1997). The Alaskan halibut fishery has been managed with individual fishing quotas since 1995. Concerns by regulators and industry that a freely tradable individual fishing quota system would lead to dramatic fleet downsizing and economic and social disruptions, particularly in fishery-dependant western Alaskan communities, led them to place tight restriction on harvest permit trading.[4] In practice, these restrictions limit the quantity of halibut that each vessel is permitted to catch, and limit fleet downsizing.

We find that although the constant harvest policy tends to over-smooth the catch relative to the optimal policy, declines in the fishery value are small. We estimate that less than 1% of the fishery value is lost due to the use of a constant harvest rate rule. The effects of the restrictions on trading quota are much more severe. By capping the maximum catch per vessel, fisheries managers have imposed a minimum fleet size for the halibut fishery. An important consequence of this regulation is that Alaskan fishermen participate in multiple fisheries in order to adequately utilize their vessel capital, and to earn a living. The scale of the problem is striking. Our sample data show that on average, vessels directed only 9.4% of their annual fishing effort to halibut in 1997, the year of our data. Because these vessels constantly move between fisheries, nontrivial capital adjustment costs are incurred in refitting boats to harvest different species, in some cases with different gear. We estimate that the additional costs incurred as a result of this policy reduce the value of the fishery by as much as 40%. This loss in value results from harvesting the annual catch with a part time fleet that is nearly 10 times larger than its efficient level, i.e., relative to the case where vessels specialize in halibut year round. A significant part of these losses accrue due to socially wasteful adjustment costs which are incurred as vessels regularly switch between fisheries. The extent to which these refit costs affect the value of fisheries has not been previously emphasized in the literature.[5]

[4] See DiCosimo, 2004; Pautzke and Oliver, 1997; Committee to Review Individual Fishing Quotas, 1999.

[5] An exception is Weninger and Waters, 2003, who report that in response to strict regulations on red snapper fishing, fishermen in the Gulf of Mexico regularly incur refit costs to harvest non-reef fish species such as king mackerel.

The remainder of the paper is organized as follows. Section 2 presents the theoretical model. Section 3 discusses the management program used in the Alaskan pacific halibut fishery and presents an overview of the empirical work performed to calibrate the model. Results are reported in Section 4. Section 5 summarizes the key findings and provides concluding remarks.

2 The model

This section presents a model of a fishery incorporating random fluctuations in the growth of the biological resource and costly capital adjustment. We consider a planner who jointly chooses both the capital stock and the harvest (or alternatively the escapement) with the goal of maximizing the value of the fishery.[6]

Let $t = 1, 2, ...$ index a particular fishing period. Each period is subdivided into a harvest season, and a period that is closed to harvesting. We assume that all stock growth occurs during the time the fishery is closed to harvesting. The exploitable biomass in period t is denoted x_t. We assume that x_t is observed with certainty at the time that harvest quantity h_t is chosen.[7] Period t escapement is $s_t = x_t - h_t$, where $h_t \in [0, x_t]$ is the period t catch. Escapement is nonnegative and cannot exceed the available biomass; $s_t \in [0, x_t]$.

[6] Four U.S. fisheries are managed under systems of tradeable quota, which establish property rights and exhibit well functioning markets in quota. Under these conditions, the capital stock would be determined optimally, and in the absence of commitment issues or other related concerns, a manager with control of the aggregate harvest would be able to achieve the first best.

[7] While common in the literature (Reed, 1979), the assumption that x_t is observed without error does not describe real world fisheries management. An analysis of the effects of stock mismeasurement is reserved for future work. The assumption that harvest is selected after observing the realisation of random stock growth is somewhat representative of the actual timing of events in the halibut fishery, where biologists at the International Pacific Halibut Commission derive a Bayesian updated estimate of x_t prior to the selection of h_t.

Fish stock growth is density dependent, and is influenced by random growth conditions in the ocean environment. Following Reed (1979) and others, we assume that growth shocks enter multiplicatively;

$$x_{t+1} = z_{t+1}G(s_t), \tag{1}$$

where $G(\cdot)$ is deterministic growth satisfying $G'(0) > 0$, $G''(.) \leq 0$,and z_t is a mean 1 random variable with finite support $[\underline{z}, \overline{z}]$, where $0 < \underline{z} < \overline{z} < \infty$. The random component, z_t, is assumed to follow a Markov chain with known transitions. In our empirical application to the pacific halibut fishery shocks will be serially correlated. Consequently, the conditional distribution of the $t+1$ shock depends on z_t. We examine the possibility that the shocks are independently distributed as a special case in section 4.

The stock growth model implies an intermediate level of abundance at which expected per-period growth is maximized. Density dependent growth introduces a cost to harvest smoothing in the form of reduced expected yields. While, in principle, the planner chooses the escapement $s_t = x_t - h_t$, a reduction in the variation of escapement can only be achieved by allowing wider fluctuations in the harvest. For example, the planner could choose to set s_t to a constant, in which case, expected yield would be large but all of the stochastic growth would be absorbed by the harvest. Alternately, the planner could choose a constant harvest $h_t = h$, for all t in which case escapement will vary in response to changing stocks, and average yield would be smaller.

The harvest benefit is $B(h_t)$, where $B(\cdot)$ is a concave function of the total catch. If the consumer demand for fish is less than perfectly elastic $B(\cdot)$ will be a strictly concave function.

The harvest technology utilizes a single capital input denoted k_t in period t. For concreteness k_t will represent the number of fishing vessels in the harvest fleet. Capital is an essential and normal input in the harvesting process. Individual vessel harvesting costs are assumed increasing and strictly convex in catch, and non-increasing in the stock abundance. Fleet level harvesting costs are denoted $C(h_t, k_t, x_t)$. Our assumptions for vessel-level costs imply that for fixed k_t, $C(h_t, k_t, x_t)$ is strictly convex in h_t and non-increasing in x_t.

The vessel capital (i.e., boats) can be moved in and out of the fishery but capital adjustment takes time and is costly. We assume a one period delay is required before capital investment is operational. The productive capital stock in period $t + 1$ is equal to the depreciated period t capital stock plus investment, which we denote i_t:

$$k_{t+1} = (1 - \delta)k_t + i_t,$$

where $\delta \in [0, 1]$ is the capital depreciation rate.

Fishing vessels cannot be costlessly reallocated to uses outside of the fishery.[8] For example, capture gear is often specific to a particular species of fish, and the skills of the captain and crew are developed to operate a particular gear type, target a particular species of fish and operate within specific geographical boundaries.[9] Specificity of physical and human

[8] Clark, Clarke, and Munro (1979), Matulich, Mittelhammer and Roberte (1996), and Weninger and McConnell (2000) have emphasized the importance of non-malleability of fishing capital.

[9] Knowledge of the location of fish across space and time is essential for a successful fishing operation. This knowledge may take years to acquire and likely involves costly investments in information, i.e., costly search which generates information but not necessarily a saleable catch. While some skills may be transferable to

fishing capital is appropriately modelled as non-convex capital adjustment costs. We allow for a wedge between the capital *purchase* and *resale* price, which we denote p_k^+ and p_k^-, respectively. Further, we assume that $p_k^+ > p_k^-$. The difference between the purchase and resale price introduces the capital adjustment cost.

Subject to the constraints described above, the social planner chooses the annual harvest and capital investment to maximize the expected present discounted value of the fishery:

$$\max_{\{h_t, i_t\}} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t [B(h_t) - C(h_t|k_t, x_t) - p_k i_t] \right\}, \tag{2}$$

where E_0 is the expectations operator conditional on currently available information, β is the discount factor, and p_k denotes the price of capital:

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

It is instructive to review the timing of the harvest and investment decisions and the information available when decisions are made. At date t, the manager observes the exploitable biomass x_t and the number of boats k_t in the fishing fleet. Because past escapement s_{t-1} is known, the current period shock z_t is also known.[10] Except for the special case of independent shocks, the current shock z_t is a state variable in the model. Summarizing, the

other fisheries, knowledge about the location fish within the geographical boundary of the fishery is likely to have discretely lower, possibly zero, value elsewhere.

[10] In the pacific halibut fishery the growth of the stock is affected by surface water temperatures that follow decadal oscillations (Clark et al., 1999). Water temperatures are easily measured and thus the assumption of observable shocks is not unreasonable.

period t choices variables are (i_t, h_t) and period t state variables are (k_t, s_t, z_t), where k_t and s_t are previously chosen and z_t is exogenously determined. Notice that harvest in period t determines s_{t+1}, and the investment can be expressed as a choice of k_{t+1}. Adopting standard dynamic programming literature notation: $(k_t, s_t, z_t) \equiv (k, s, z)$ and $(k_{t+1}, s_{t+1}) \equiv (k^{'}, s^{'})$, the management problem can be formulated as a recursive problem with Bellman equation given by:

(3)

$$V(k, s, z) = \max_{k', s'} \left\{ B(zG(s) - s') - C(zG(s) - s'|k, zG(s)) - p_k \left(k' - (1 - \delta) k\right) + \beta EV(k', s', z') \right\},$$

where $EV(k', s', z')$ represents the optimized expected value of the fishery.

The solution to the problem in 3 is pair of policy functions $s' = S(k, s, z)$ and $k' = K(k, s, z)$ which describe the optimal one-period-ahead choice of k' and s' for all possible current states (k, s, z). We solve for $V(.)$, $S(.)$ and $K(.)$ numerically using Value Function Iteration (Judd (1998) provides a complete discussion of Value Function Iteration). The numerical technique entails first discretizing the state space and then iterating on the Bellman equation, starting with an initial guess for the value function. It can be shown (see Stokey and Lucas (1989)) that the iterative process converges to the true value function. Subsequently, we use information on the distribution of z along with the optimal policy functions to compute the invariant joint distribution of (k, s), which is then used to obtain various statistics of interest (see Doyle, Singh and Weninger (2005) for additional details).

3 Application to the Alaskan Halibut Fishery

We apply the model and solution technique outlined above to the Alaskan pacific halibut fishery. In this section we provide an overview of the fishery along with a discussion of the empirical work used to tailor the more general theoretical model of the previous section to this 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.[11] A 1923 convention between Canadian and U.S. Governments lead 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.

A three step process determines the annual halibut catch. Following each harvest season (March 15 through November 15), data on commercial catch and effort (the number and time that baited lures are left to soak on the sea bottom) is collected and analyzed by the IPHC. This data, and in some years independent survey data, are used to generate a Bayesian updated estimate of halibut stock abundance across its range. Based on this stock assessment the IPHC scientists put forth catch recommendation for the upcoming harvest season. The IPHC recommendation is made available to the public. An annual meeting is scheduled prior to the season opening at which time members of the public, and of course

[11] Crutchfield and Zellner (1962) provide an extensive survey of the management and historical development of the fishery.

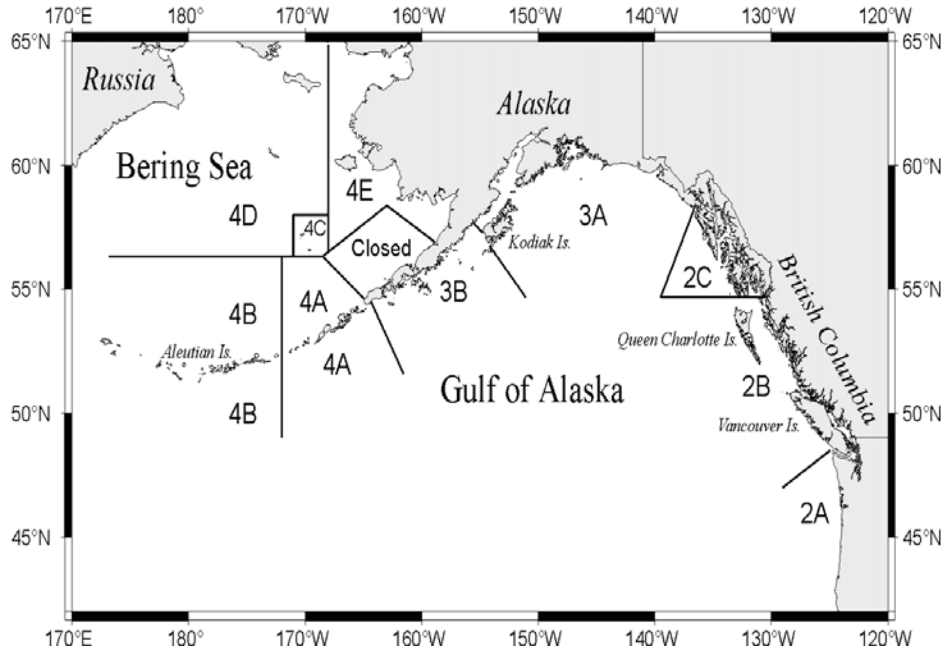

Figure 1: Management Units in the Pacific Halibut Fishery

fishermen are invited to comment on the IPHC recommendation. The IPHC board members then select the next-period harvest. Currently, the halibut stock is managed under a constant harvest rate policy wherein allowable annual removals are determined as a constant fraction of the estimated exploitable biomass.[12]

Prior to 1995, command and control regulations were used to ensure that annual harvest levels were kept in check. Restrictions on the length of the fishing season were used to limit the total catch of the fleet. Fleet size was not restricted. The pacific halibut fishery is a often cited example of the failures of command and control management. Because entry of new vessels was not restricted, the size of the fleet grew unabated, leading to increasingly

[12]A constant harvest rate policy is suggested for pacific halibut fishery by Sullivan, Parma and Clark (1999), “because this kind of strategy has been shown to achieve close to optimal yields in the face of long-term changes in productivity such as exhibited by pacific halibut”.

shorter halibut seasons. In 1994 for example, the bulk of the U.S. annual halibut catch was harvested in 2 six hour openings.

Short season lengths, a dangerous race for fish, and economic waste spurred the adoption of property rights-based management approach in 1991 for the Canadian fleet and in 1995 for the U.S. fleet. Individual fishing quotas or IFQs grant their owner exclusive rights to harvest shares of the annual halibut catch. Halibut quota shares were initially allocated gratis to 5,484 vessels owners and leaseholders that had verifiable commercial halibut landings during 1988-1990.[13]

Designers of the U.S. rights-based program were concerned that unrestricted transferability of IFQs would lead to significant geographical redistribution of harvesting activity, consolidation of IFQ ownership, and a change in fleet structure, away from the historical small-boat fishery concentrated in western Alaskan coastal communities, to a larger boat fleet fishing from non-Alaskan ports, in particular Seattle, Washington. In response, restrictions on transferability and ownership were included in the initial program design. Caps were placed in the amount of IFQ that single individual can own (0.5% of the total quota in any region and for all regions combined). A complex system of *blocking* was adopted which effectively limits the quantity that can be harvested from a single vessel. In addition, a requirement that the owner of the IFQ be on board the vessel when fishing takes place was imposed. Transferability across vessel size classes is restricted so that harvesting responsibility cannot be concentrated on the largest boats in the fleet.

[13] See Committee to Review Individual fishing Quotas (1999) for additional discussion of the operation of the US rights-based management program. See Grafton, Squires and Fox (2000) for information on the Canadian rights-based management program and its effects.

3.1 Model calibration

We have argued that the optimal management policy must strike a balance between costs that result from large fluctuations in the catch, and foregone stock growth which results under large variation in escapement. The optimal amount of catch smoothing is thus an empirical matter that depends on the *shape* of the four main model components: (1) the harvest benefit function, (2) the fleet harvesting cost function, (3) vessel capital adjustment costs, and (4) the halibut stock growth function.

We calibrated the model to the Alaskan pacific halibut fishery. Efforts were made to use the best available data and appropriate econometric methods. Due to space limitations, we present an overview of the empirical analysis and results. A detailed discussion of the calibration is available in Doyle, Singh and Weninger (2005).

We obtained an estimate of the own-price halibut demand elasticity from a recent study by Herrmann and Criddle (2005). Remaining model components are estimated using data from: 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 a survey of vessel captains, and other information from fishermen and managers at the IPHC.

Data limitations: Harvest cost data are available in for Alaskan halibut fishermen only. While Canadian boats use similar capture techniques, extrapolation of U.S. fleet cost estimates is problematic. For example, the distance between the vessel's port and the halibut fishing grounds, an important factor in variable harvesting costs, varies across regions. Extrapolating US-based harvest costs to the Canadian fleet could bias the results. Furthermore, stock abundance data for management units 3B and 4 are unavailable.

Complete cost information for 102 vessel observations were 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).

These data limitations force us to focus our calibration on class 2 vessels and management unit 3A. Class 2 boats harvest the largest share of the total Alaskan catch (on average 54.92% during 1995-2002). Unit 3A produces roughly 55% of all commercial harvests (U.S. and Canada), is well-represented in our 1997 harvest cost data, and has relatively complete information on stock abundance.

Harvest benefit function: Herrmann and Criddle estimate the own-price halibut demand flexibility for the period 1976-2002 in the U.S. wholesale market (the main market for pacific halibut), at -0.29. Following Herrmann and Criddle we assume a linear inverse demand for halibut, $P(h_t) = a - bh_t$. Using consumer surplus as a measure of consumer welfare, the total benefit from the halibut harvest h_t in period t is the sum of consumer surplus plus fishing industry revenues;

$$B(h_t) = ah_t - \frac{1}{2}bh_t^2, \tag{4}$$

where benefits are denoted in 1997 dollars (all subsequent values are also in \$1997). Parameter estimates for a and b are reported below in Table 1.

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 at roughly 18 foot intervals. The long line is soaked and then 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 to consumer retail markets and restaurants.

The main variable operating expenses are from fuel, bait and ice, and food and supplies for the captain and crew, and lost gear. It is reasonable to assume that variable costs increase, possibly sharply, as harvest quantity approaches a maximum or peak harvest level for a vessel operating during a single harvest season. Limited space on board the vessel restricts crew size, and steaming time to and from the fishing grounds limits the number of trips that can be taken in a given calendar period. A cubic functional form is specified to allow a flexible relationship between costs and catch;

$$c(q_t|x_t) = FC + c_1 q_t + c_2 q_t^2 + c_3 q_t^3 + c_x x_t. \tag{5}$$

FC denotes annual fixed costs which include expenses for vessel mooring and storage, permits and licence fees, and fees for accountants, lawyers, office support, and routine maintenance and repairs. We include the labor services of the captain and crew as a fixed cost component. 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 particular crew size. On occasion crew size may be increased or decreased but adjustments tend to be infrequent.

Capital adjustment costs: Harvesting capital likely has low value if used outside of fishing. However, boats are mobile, and there numerous fisheries in addition to halibut in which a vessel and crew can be employed. We assume there is a well-functioning market for used fishing boats (in fact an active vessel resale markets exist in western North American fisheries) and set the capital salvage price, p_k^- equal to the mean self-reported resale value from our 1997 cost survey data. The wedge between the purchase and resale price is assumed the result of refitting costs.

We surveyed halibut captains to determine the average costs of refitting a vessel to fish for species other than halibut. The captains we surveyed indicated that refit costs depend largely on which fishery the vessel is moved to or from. If a vessel is moved from a fixed gear fishery (e.g., some other longline fishery), refit costs are considerably less than if the vessel is moved from a trawl gear fishery. Modelling the set of fisheries in which vessels participate is beyond the scope of this study. Instead we use the survey data to generate plausible ranges for refit costs.

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 \$27,000. If the boat is switched from a trawl gear fishery, the refit costs may increase to \$85,000. (The baseline calibration assumes the refit cost of $\$76,500$). 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.

Stock growth model: 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. Changes in the survival, growth and recruitment of young fish into the exploitable population are tracked by a computer-based model which incorporates 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, weight at age, among other factors (see Sullivan, Parma, and Clark, 1999). Each year new data are collected from commercial and survey sources and the number of fish and average weight at age by sex and age is re-estimated using a Bayesian updating procedure.

The computational time required for Value Function Iteration increases exponentially with the number of state variables. Adopting the sex and age specific IPHC stock model directly would increase the number of state variables to well over 50 and thus was not practical. Our approach is to fit a simpler parametric model to characterize the halibut stock growth. For this purpose we aggregate across sex and age classes to obtain estimates of the pre-harvest exploitable biomass, x_t, catch, h_t and the escapement, s_t, for management unit 3A during 1974-2003. The Logistic growth function, $G(s_t) - s_t = \alpha s_t(1 - s_t/x^c)$, is fit to the data using an iterative feasible generalized least squares procedure.[14]

The state space for the random shock z_t and the Markov transition matrix are calculated following Judd (1998, p. 85-88). A complete discussion of the model calibration is available in Doyle, et al. (2005a). Table 1 summarizes the calibration results.

[14] The model provided a good fit to the 1974-2003 data, although because the data is itself generated from a model, formal tests of fit, or analysis of alternate empirical specifications is not possible. Note that similar results were found under a Ricker growth function.

Component	Functional form	Base Case Parameters
Harvest Benefits	$B(h_t) = b_1 h_t - \frac{1}{2} b_2 h_t^2$	$b_1 = 2.9854; b_2 = 3.6e^{-4}$
Fleet Costs Vessel Costs	$C(h_t\|k_t, x_t) = k_t \cdot c(q_t\|x_t)$, $q_t = h_t/k_t$ $c(q_t\|x_t) = FC + \sum_{j=1}^{3} c_j q_t^j + c_x x_t$	$FC = 177.951;\ c_1 = 0.130$ $c_2 = -0.387e^{-3}; c_3 = 0.750e^{-6};$ $c_x = -.484e^{-3}$
Capital Price	$p_k = \begin{cases} p_k^+, & \text{if } k_{t+1} > (1-\delta)k_t \\ p_k^-, & \text{if } k_{t+1} \leq (1-\delta)k_t \end{cases}$	$p_k^+ = \$236,500;\ p_k^- = \$160,000$ $\delta = 0.1$
Stock Growth	$G(s_t) - s_t = \alpha s_t(1 - s_t/x^c)$	$\alpha = 0.283; x^c = 443,392.07$

Table 1: Model Calibration Summary.

4 Results

4.1 The optimal policy

Figure 2 plots the optimal escapement policy as a function of k and s for the case of $z = 1$, the mean value. The policy function $s' = S(k, s, z)$ is plotted for k and s values corresponding to their respective 99% confidence intervals (obtained from the invariant distribution calculation) holding z at its mean value of 1. The policy functions are shifted by different realizations of z.

Observe that optimal escapement is increasing in s and decreasing in k. When past escapement s is large and a $z = 1$ shock is realized, the current stock size is also relatively large. The large stock of fish could be harvested immediately. However, due to the costly capital adjustment, particularly in the short run, diminishing marginal net benefits suggests that it is best to increase the current escapement and *bank* some fish for future harvest. With a large fleet, the average harvesting costs rise at a slower rate as catch increases than with a small fleet. The rate at which current period marginal net benefits decline is less when k is large. As shown in Figure 2, optimal escapement (current period harvest) is inversely (directly) related to the size of the fishing fleet.

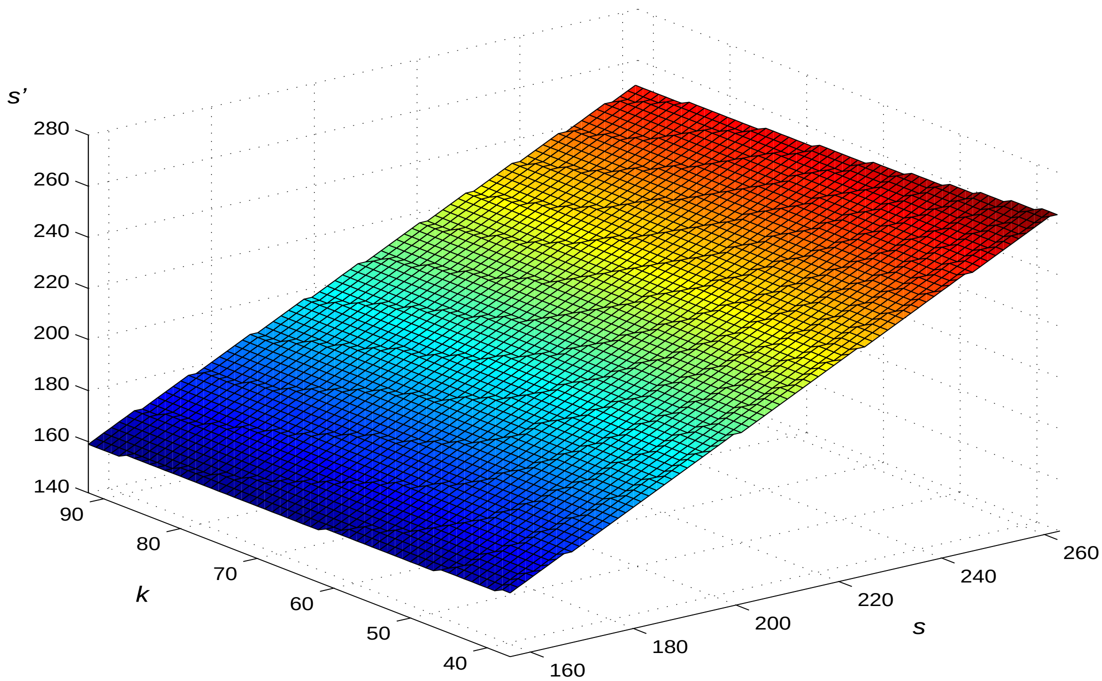

Figure 2: Optimal Escapement

The capital investment policy function is more complicated. Figure 3 reports two cross sections; panel (a) reports the optimal k' conditional on current capital k (displayed along the horizontal axis) while holding s constant at its median value (approximately 203 million pounds). Panel (b) depicts optimal k' conditional the previous escapement, s this time holding k constant at its median value of 61 boats. Both panels report results for the mean value shock, $z = 1$.

Consider panel (a) in Figure 3 first. Recall that as the current fleet size increases, moving left to right in the figure, escapement declines (see Figure 2). Consequently, future expected harvest declines with larger current capital which implies that the expected marginal value of capital declines with k. The number of boats that is *added* to the fleet is thus also declining

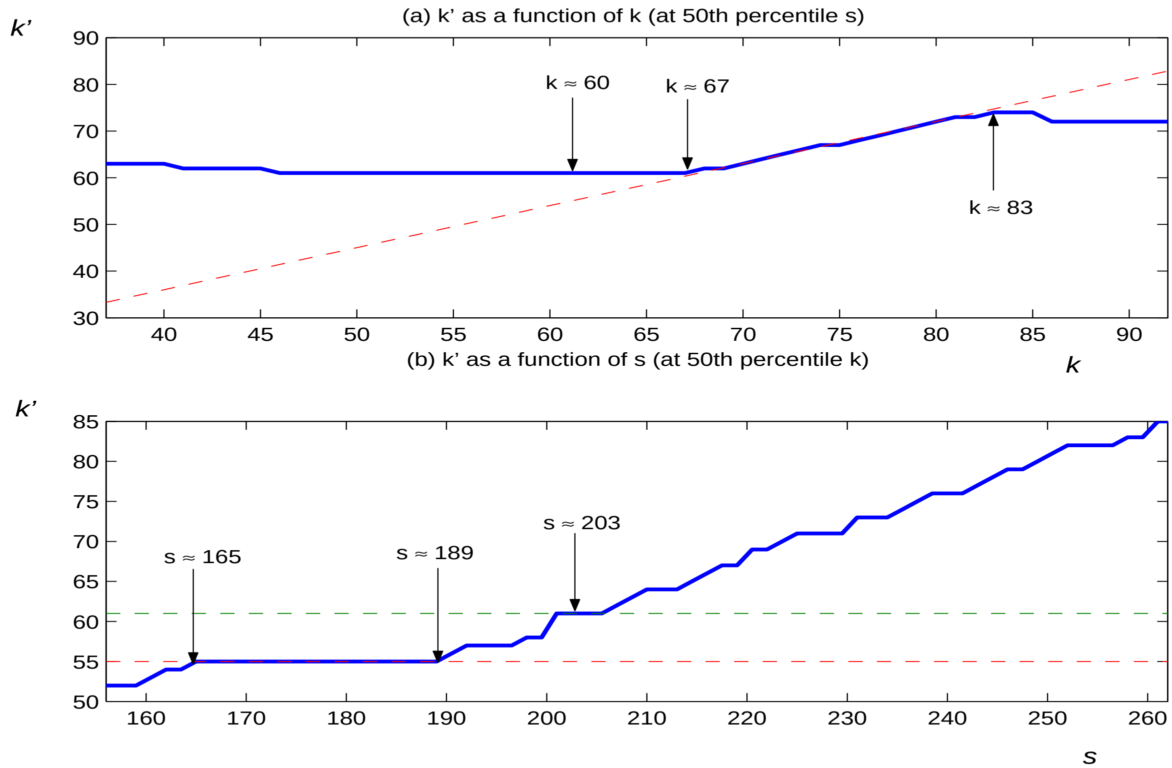

Figure 3: Optimal Investment

in current capital k (this effect can be seen most clearly for k between 40 and 46 boats and for k between 83 and 90 boats).

To assist in interpreting the results, the dashed line identifying zero net investment, $k' = (1-\delta)k$, is shown in panel (a). For $k < 62$ both gross investment, $k' - k$, and net investment, $k' - (1-\delta)k$, are positive. This is because at small fleet sizes and average stock abundance, the expected marginal value of fishing capital exceeds the capital purchase price, p_k^+ and investment in additional boats is optimal. For fleet sizes between roughly 61 and 67 boats, gross investment remains positive however the rate at which capital is added is less than depreciation so that net investment is negative. For fleet sizes between roughly 67 and 83 boats, net investment is zero. In this region the expected marginal value of capital lies in the interval $[p_k^-, p_k^+]$, and the optimal action for the manager is to neither invest nor divest capital from the fishery. At $k \geq 83$, divestment is optimal since the expected marginal value the current capital stock is below the capital salvage price p_k^-.

Turn now to panel (b) in Figure 3. To assist in interpreting the results, a dashed line has been drawn at the current capital level, $k = 61$ boats, and at $(1 - \delta)k$ roughly equal to 55 boats. At escapement levels below 165 million pounds, future expected catch is low and the expected marginal value of capital, corrected for depreciation, is below the salvage price p_k^-. In this region of escapement it is optimal to divest boats from the fishing fleet. For escapement levels between roughly 165 and 189 million pounds, the expected marginal value of capital (at $k = 61$) lies between the capital salvage and purchase prices. As in panel (a), investment inactivity is prescribed. At $s \approx 189$ million pounds, gross investment becomes positive, however boats are added are a rate less than depreciation; the expected marginal value of *effective* capital is maintained at p_k^+. At $s \approx 203$ million pounds and larger, the expected marginal value of capital exceeds p_k^+ and net investment is positive.

In addition to studying the policy functions, we can generate further insights into the properties of the model by examining the invariant distributions of control and state variables, and by analyzing the effects of key parameters on these distributions. Table 2 reports mean values, standard deviations, and 99% confidence intervals for capital, escapement, harvest, catch per boat (h/k), the harvest rate (h/x), industry profits, and consumer surplus. The results for the baseline calibration are presented in column 1 of the table. Columns 2-5 report the results under alternative model specifications.

Intuition for the results is best served by comparing the base case with alternate model

	1	2	3	4	5
	Baseline calibration	High capital cost	Max. indus. profits	High discount factor	iid shocks
Capital (boats)	61.76^{a}	52.70	63.95	52.11	61.45
	(10.97)^{b}	(8.68)	(9.47)	(9.33)	(7.10)
	[37,92]^{c}	[32,74]	[42,90]	[30,76]	[44,80]
Escapement (mill. lbs.)	203.91	203.23	240.65	156.45	203.86
	(21.06)	(21.95)	(31.84)	(18.35)	(14.95)
	[156.0,262.5]	[153.0,264.0]	[156.8,346.0]	[115.0,208.0]	[168.0,244.5]]
Harvest (mill. lbs.)	31.08	31.05	30.45	28.61	31.01
	(4.94)	(4.87)	(2.69)	(4.75)	(3.24)
	[19.16,43.98]	[19.50,43.50]	[22.14,35.80]	[17.48,41.43]	[22.26,39.81]
Harvest rate (%)	13.16	13.19	11.34	15.38	13.18
	(.75)	0.71	(.75)	(.82)	(.51)
	[10.68,14.52]	[10.86,14.51]	[9.26,12.76]	[12.82,16.92]	[11.68,14.27]
Catch/Boat (thous. lbs.)	505.49	560.36	480.56	550.57	505.59
	(25.49)	(25.0)	(31.70)	(22.29)	(22.88)
	[435.30,570.67]	[514.40,649.50]	[385.10,553.58]	[489.87,608.08]	[443.90,565.29]
Indus. Profit ($ mill. 1997)	47.99	44.63	49.47	45.31	48.36
	(3.33)	(4.19)	(2.93)	(3.53)	(2.20)
	[36.75,53.61]	[32.22,52.03]	[40.54,56.57]	[33.98,51.38]	[41.46,52.66]
Cons. Surplus ($ mill. 1997)	17.83	17.78	16.82	15.14	17.51
	(5.60)	(5.51)	(2.88)	(4.99)	(3.75)
	[6.60,34.81]	[6.83,33.98]	[8.83,23.06]	[5.50,30.90]	[8.92,28.55]

Table 2: Sensitivity Analysis. a- denotes mean value, b-denotes standard deviation, c-denotes 99 % confidence intervals.

specifications; columns 2-5 of Table 2.

Column 2 of Table 2 reports results under a higher capital price, and a larger wedge between the purchase and salvage price. Our survey of vessel captains indicated that price of a new fully equipped fishing vessel is roughly $800,000 and that a vessel that is scrapped for metal and parts would fetch roughly $25,000. Column 2 reports the results for $p_k^+ = \$800,000$ and $p_k^- = \$25,000$ (the base case prices are $p_k^+ = \$236,500$ and $p_k^- = \$160,000$). The primary effects of this change, as might be expected, are a reduction in the volatility of the capital stock and a corresponding increase in the volatility of catch per boat. Essentially, as it becomes more costly to adjust to changes in the catch by changing the number of boats (i.e., adjusting along the extensive margin) we see a greater tendency for movement along the average cost curves of individual boats (more of the adjustment occurs on the intensive margin). Since the increase in the costliness of capital reduces the overall *economic* flexibility, it is also optimal to reduce the volatility of the catch to some degree, which implies that the volatility of escapement must rise and expected yields decline. Consumer surplus changes very little under the higher capital costs however, as expected, industry profits and the average unit resource rent declines.

Column 3 of Table 2 reports results for the case where the fishery is managed in order to maximize the present discounted value of industry profits, instead of total benefits (industry profit plus consumer surplus). The harvest payoff in this case is more concave than in the baseline model because marginal industry profits decline more rapidly than marginal total benefits. Not surprisingly, the main effect is an increase in the standard deviation of escapement and a reduction in the standard deviation of the catch. The increased concavity in the current period payoff function induces greater catch smoothing at a cost of increased escapement volatility. Also, if the consumer surplus is not valued by the fisheries manager, the response is to leave more fish in the sea (i.e. mean escapement goes up and mean catch goes down). This is because the costs of harvesting fish declines with increased stock abundance. When consumer surplus is ignored, the incentive to leave more fish in the sea to reduce costs becomes relatively more important.

Columns 4 and 5 of Table 2 report results under a higher discount factor, and for the case of identically and independently distributed (iid) shocks. A higher discount factor effects model variables in expected ways: escapement declines to raise the expected rate of return on investment in the *in situ* stock to equal the higher interest rate (recall that the discount factor is the inverse of 1 plus the interest rate). The real price of capital has increased and fewer boats are employed in the fishery. Consumer surplus and industry profits are smaller due primarily to the higher discounting of future returns.

Turn now to the results for the iid shocks (column 5 of Table 2). First notice that the state variables reduce to (k, s) since the distribution of z' does not depend on z under iid shocks. The main effect on the results, relative to the base case, is to reduced the variance of the remaining state and control variable, as well as the corresponding welfare measures. Under independent shocks the probability of observing a sequence of low or high shocks is reduced and s and k spend less time in the tails of their respective distributions. This suggests that there will be fewer costly *adjustments* required to maintain the state variables at value maximizing levels. However, the optimal management policy adjusts control variables in order to enhance payoffs and mitigate losses when state variables are pushed to extremes. A comparison of the welfare measures under iid shocks and the baseline model indicates only small changes in industry profits and consumer surplus.

Overall the results reported in Table 2 contain few surprises. Factors that increase the concavity of the net benefit function lead to more smoothing of the catch. Increased capital adjustments costs lead to slight reductions in catch variability and slight increases in variability of escapement. The variability of the control and state variables is reduced under iid shocks, but the impact on harvest, catch per boat, and welfare is small.

Finally, we can use our model to discuss the value of the fishery, $V(k, s, z)$. Like the policy functions described above, the fishery value depends on initial state variables k, s, and z. Our results show that the value function is increasing in the starting level of the escapement. This is not surprising, since large s means higher expected future stock levels.

This is at least weakly preferable to a low initial stock level since, a manager faced with an abundance of fish in the sea, always has the option to not harvest more fish than desired in which case the fish stock will grow to its natural carrying capacity. The value of the fishery is also increasing in the starting level of the capital stock. This might seem surprising given the problems associated with the overcapitalization of many ocean fisheries, but observe that in our model the initial capital stock represents an endowment, and the planner always has the option of selling off any unwanted boats. As long as the capital salvage price is strictly positive, additional boats increase the value of the fishery.[15] To provide context for the results that follow we calculate the mean of the value function invariant distribution which is \$1.646 billion.

4.2 Actual management policy

This section analyzes the actual management policy in the Alaskan pacific halibut fishery. We characterize the management regime as exhibiting two main departures from the optimal policy. First, the fish stock is managed using a constant harvest rate (hereafter, CHR) rule, by which the catch is set to equal a fixed percentage of the existing stock. In the notation of the model in Section 2, $h_t = \theta z G(s) = \widehat{H}(s,z)$, where $\theta \in [0,1]$. Second, due to the restrictions placed on the trading of harvest quota, the number of boats is bounded from below. To carry out the analysis we require an estimate of the regulated minimum fleet size. DiCosimo (2004) reports that the restrictions on harvest permit trading impose a minimum fleet size in the entire halibut fishery, all regions and all vessel classes, of 1,050 boats. This

[15] Since the model deals with the aggregate value of the fishery, complications involving the distribution of benefits, which may be substantial in real world fisheries, do not arise here.

estimate cannot be translated directly to our calibration which focusses on area 3A and class 2 vessels. However, we can capture the *intent* of the regulation in our model. The average annual harvest of halibut in Alaskan during 1995-2002 was 50.945 million pounds. On average, class 2 boats harvested 54.92% of this total and numbered 50% of the halibut fleet. The restrictions on quota trading were designed such that class 2 boats harvested no more than 53,295 pounds of halibut annually: the minimum number of class 2 vessels is $0.5 \times 1,050 = 525$ boats and $0.5492 \times 50.945 = 27.98$ million pounds, which implies a 53,295 pound per vessel maximum catch. Scaling this intended catch per boat to match the sustainable harvest quantities from Table 2 suggests a regulated minimum fleet size of 583 vessels.

The effect of this policy is to maintain a large fleet size than needed to harvest the yearly catch. As a result most vessels in the fleet spend only a small fraction of the year employed in the halibut fishery and participate in other fisheries the rest of the year. The baseline model discussed in the previous section was solved under the assumption that all boats employed in the halibut fishery would fish there full time. Our data indicates that vessels spend a small fraction of the year fishing for halibut (the sample mean is 9.4%). There are two adjustments we need to make to the model to account for this. First, since each boat spends only a fraction of the year in the halibut fishery, our estimate of the fixed costs associated with operating a boat is too high–essentially we have attributed 100% of the fixed costs of operating a boat to the fraction of the year spent in the halibut fishery. In order to make a fair comparison, we scale down the fixed costs of operating a boat proportional to the mean fraction of time spent fishing halibut. Second, we have to add refitting costs to the adjusted fixed costs of operating the boat as each boat must be refitted to catch halibut whenever it

	1	2	3	4
	Opt. Harvest Opt. Capital	Best CHR Opt. Capital	Opt. Harvest Fixed Capital	Best CHR Fixed Capital
Capital (boats)	61.76[a]	61.86	583	583
	(10.97)[b]	(10.14)	(0)	(0)
	[37,92][c]	[39,91]	*na*	*na*
Escapement (mill. lbs.)	203.91	207.12	214.62	210.28
	(21.06)	(27.60)	(18.98)	(27.68)
	[156.0,262.5]	[142.5,280.5]	[171.0,267.0]	[145.5,283.5]
Harvest (mill. lbs.)	31.08	30.96	31.29	31.01
	(4.94)	(4.13)	(5.14)	(4.11)
	[19.16,43.98]	[20.90,42.06]	[18.95,44.58]	[21.09,41.74]
Harvest rate (%)	13.16	13.00	12.64	12.85
	(.75)	(0)	(.89)	(0)
	[10.68,14.52]	*na*	[9.88,14.27]	*na*
Catch/Boat (thous. lbs.)	505.49	503.42	53.61	53.18
	(25.49)	(29.21)	(8.82)	(7.05)
	[435.30,570.67]	[428.49,581.77]	[32.51,76.47]	[36.18,71.59]
Indus. Profit ($ mill. 1997)	47.99	48.30	25.91	25.80
	(3.33)	(2.94)	(4.78)	(4.54)
	[36.75,53.61]	[38.72,54.40]	[10.38,33.00]	[11.97,34.34]
Cons. Surplus ($ mill. 1997)	17.83	17.56	18.10	17.61
	(5.60)	(4.68)	(5.87)	(4.66)
	[6.60,34.81]	[7.86,31.84]	[6.47,35.77]	[8.01,31.36]

Table 3: Constant Harvest Policy. a-denotes mean, b-denotes standard deviation, c-denotes 99 % confidence intervals.

moves into the halibut fishery from another fishery. Given that the average boat spends only a small fraction of the year fishing halibut, we assume that these refitting costs are incurred yearly. Rather than rely exclusively on the data received from our informal survey of halibut captains, we calculate the percentage of the fishery value lost over the range of reported refit costs.

Finally, to isolate the underlying source of management problems we analyze the CHR rule and fixed capital policy in isolation before considering their combined effects.

Column 1 of Table 3 repeats the results under the optimal policy. Columns 2-4 of Table 3 report results under alternative management rules. All results in Table 3 are for the baseline calibration.

Column 2 reports the results under a CHR rule and the optimal capital investment policy, i.e., conditional on the employing the CHR harvest rule, we solve for the optimal capital investment policy. This scenario represents the case where the IPHC continues to select the annual catch following the CHR, and all quota trading restrictions are removed. The reported harvest rate (13.00%) is chosen to maximize the value of the fishery. In general, the optimal CHR will depend on the starting values of k and s. Since we do not have probabilities over the initial values of k and s, we analyze the optimal constant harvest rate policy for a range of possible starting values. In practice, the optimal constant harvest rate policy did not depend strongly on the choice of initial conditions.

Comparing the results in column 1 and 2 of Table 3 finds that the CHR rule has only small effects on the invariant distributions of the model variables, and on welfare measures. This is not surprising, given that the optimal policy (Figure 2) is quite linear in escapement and depends only weakly on capital. The mean and the standard deviation of escapement is higher under the CHR rule. The lost flexibility for adjusting harvest explains this finding. Under the optimal policy the catch rate h/x can be reduced for example if abundance has declined due to a sequence of unfavorable shocks, or increased if favorable shocks lead to high abundance. Under the CHR rule, the harvest is higher (smaller) when abundance is large (small), however, the manager cannot adjust the harvest rate in response to stock abundance. The result is a more widely dispersed escapement distribution and lower yields on average, although the yield loss is small.

A comparison of the value functions finds that managing the fishery with an optimally chosen CHR and optimal capital investment implies a cost of less than one percent of the fishery value. From these results we conclude that the CHR rule is a reasonably good approximation to the optimal harvest policy in this fishery.

Column 3 of Table 3 reports the results for the case of an optimal harvest policy but under a fixed fleet size of 583 vessels, i.e., we solve for the harvest policy that maximizes the value of the fishery conditional on k being fixed at 583 boats. This experiment isolates the effect of the quota trading restrictions under the current management program.

Notice that the mean escapement is higher and less variable than under the optimal policy. Under a large fleet, the harvest cost savings from maintaining a large stock sizes become important. The reduced variability of escapement is explained by *flattening out* of the harvest net benefit function under a 583 boat fleet. Observe that on average the catch per boat is a mere 53.67 thousand pounds, which is only 10.6% of the catch per boat under the optimal policy. Variation in the catch per boat imply modest changes in marginal harvesting costs and consequently, the incentive to smooth the escapement in order to maintain higher expected yields is important. The mean harvest is increased slightly, as is the standard deviation of the harvest. Turning to the economic welfare measures, we find that mean consumer surplus increases slightly. Industry profits under the large and fixed harvest fleet are roughly half of the profits under the optimal policy. This profit reduction is the result of a small catch per boat and corresponding high average harvesting costs.

Column 4 of Table 3 reports the result under a CHR rule, and a fixed fleet size. These results are intended to represent the current management program in the Alaskan pacific halibut fishery. The results in column 4 are very similar to column 3. This is not surprising. We have already seen that the optimal escapement policy closely resembles a constant harvest rate policy, and in this case there is no variability in capital, suggesting that the optimal and CHR cases will be virtually identical.

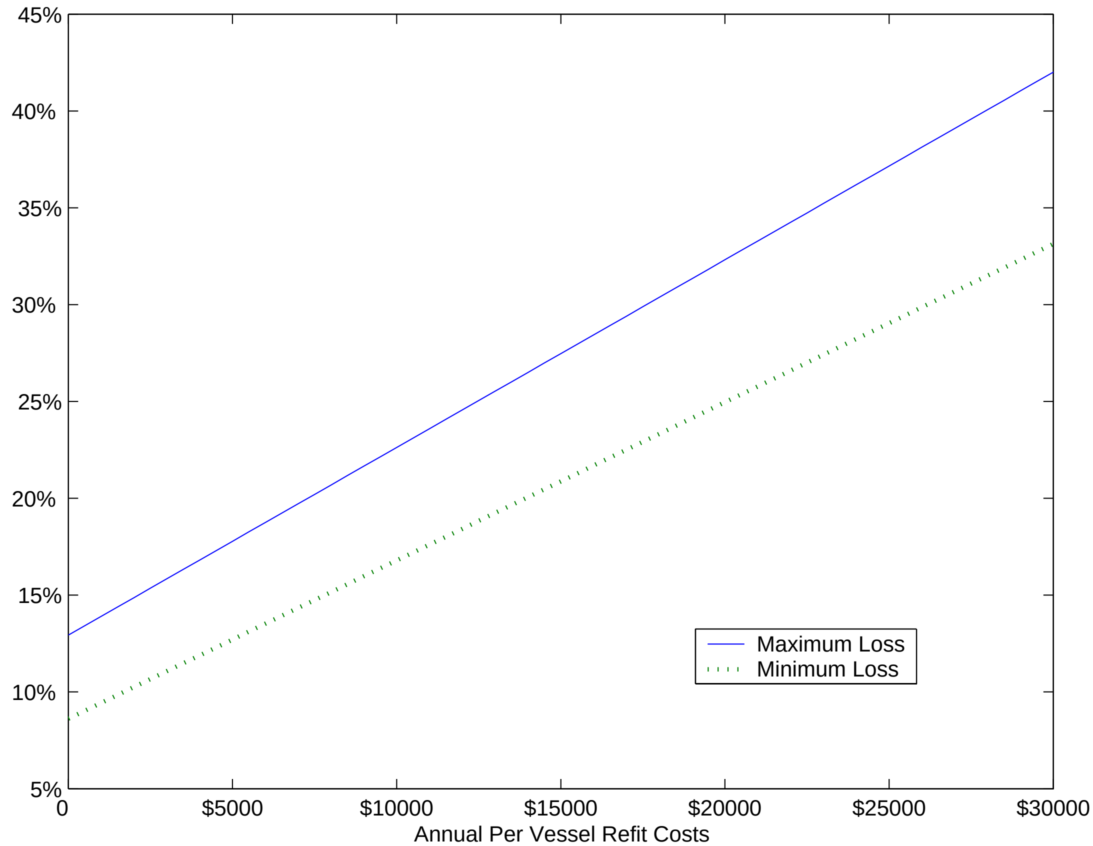

Figure 4: Lost Fishery Value Due to Vessel Refitting

Figure 4 reports the percentage of the value of the fishery that is lost under capital refitting cost which range from $\$0 - \$30,000$. The losses reported in the figure include both the costs associated with fixing the fishing fleet at 583 part time vessels as well as refitting costs incurred. Even in the absence of refitting costs, the loss associated with a fishing fleet fixed at 583 part time vessels would be approximately 9-13 % of the value of the fishery, where the exact percentage depends on the initial values of s and z (and for the optimal policy, k). This loss is due to the fact that with a fleet size of 583 boats, individual vessels harvest less than their average cost minimizing quantity and fleet level costs are higher than under the optimal policy.

As indicated in the figure, losses rise as refit costs rise. If on average annual refit cost are \$27,000, which is the median value for class 2 vessels reported in our survey of halibut captains, the losses range between 20% and 28% of the value of the fishery. If the refit costs were as low as \$6,000 per year (\$6,000 is the lowest value reported by surveyed halibut captains) the loss remain significant, ranging from 13-19% of the value of the fishery. Even for refit costs below those reported in our survey, the losses due to restrictions on trading quota represent the largest distortion in the fishery, eclipsing for example, the losses that arise under a non-optimal harvest policy.

Summarizing the results, we find that for the case of the Alaskan pacific halibut fishery, a CHR rule provides a reasonable approximation to the optimal harvest rule. Reductions in the value of the fishery due to the CHR rule are less than 1%. The policy that restricts quota trading causes the harvest fleet to be almost 10 times larger than the optimal fleet size. When compared to the base case, a fishery where the number of boats is fixed at 583 is worth between 30% and 40% less than the value of the fishery managed under the optimal policy, where the exact percentage loss depends on the initial values of state variables. A large part of this loss is due to the necessity of refitting each boat once per year to harvest a limited amount of quota. Even using a much lower estimate of the refit costs, the loss in the value of the fishery under quota consolidation restrictions is significant. If the refit costs are \$6,000 per year, the lowest values reported by surveyed vessel captains, the loss ranges from $13-19\%$ of the value of the fishery.

5 Conclusion

This paper uses Value Function Iteration to solve for the optimal management policy in a fishery that faces stock growth uncertainty and capital adjustment costs. With costly capital adjustment marginal net harvest benefits diminish providing an incentive to smooth harvest over time. While excessive harvest smoothing implies increased variability of stock abundance and reduced average yields, excessive variability in the catch leads to high average harvest costs and increased capital adjustment costs. We show that the optimal policy smooths the catch to balance these trade-offs.

Our model identifies and quantifies factors that lower the value of a fishery, under realistic conditions, and thus informs the current debate about the sources of management problems in an important U.S. fishery. Contrary to the perception that U.S. fish stocks are mismanaged, we find that the halibut stock is healthy and that losses that arise from use of a constant harvest rate rule rather that the optimal harvest policy are small. Results show that losses arising from harvesting the annual catch with an oversized and part time fishing fleet could be as high as 40% of the fishery value (with conservative estimates of refit costs the lost value remains high ranging from $13-19\%$ of fishery value). The policy that maintains the halibut fleet at its current large size addresses the goal of minimizing social and economic disruption in Alaskan communities. Interestingly, a significant portion of the costs that we identify are not due to overcapitalization per se, but rather due to the necessity of regularly refitting boats to fish in different fisheries.[16] Gains could be achieved through specialization

[16] Although not considered in this paper, removing restrictions on harvest permit trading across vessel classes should also raise resource rents.

if boats participated in fewer fisheries each year. The extent to which these refit costs affect the value of fisheries has not been previously emphasized in the literature. Applying the model to analyze bioeconomic performance in other fisheries should provide further policy guidance.

Extensions of the methodology used in this paper could provide additional insights for fisheries management. For instance, we have focussed on uncertainty in stock growth, assuming throughout that true abundance is observed at the time harvest and investment decisions are made.[17] Other sources of uncertainty likely to be important in fisheries management include stock measurement error, uncertainty regarding the true stock growth function and the influence of random environmental shocks (e.g., additive versus multiplicative shocks), output price uncertainty and, from the perspective of the fisheries manager, uncertainty regarding the true cost of harvesting fish and the capital adjustment costs. Our model and the solution technique can be adopted to analyze the effects of these or other sources of uncertainty on the optimal harvest and investment policies.

Our results find that policies to reduce the oversized U.S. halibut fleet can be expected to raise resource rents, although these rent gains must be weighed against possible social and economic disruption to Alaskan fishermen. We identify what appears to be a free lunch; nontrivial benefits could be realized with the oversized fishing fleet and with minimal economic disruption, if fishermen participated in fewer fisheries each year.

[17] Clark and Kirkwood (1986) study a fishery management problem in which stock abundance is unobserved at the time the harvest decision is made and, as in our model, growth is influenced by multiplicative random shocks. Sethi, et al., (2003) add a third source of uncertainty, mismeasurement of the actual catch of the fishing fleet. These papers do not consider fishing capital investments and assume a linear-in-catch payoff from harvesting fish.

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