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Fisheries management with stock growth uncertainty and costly capital adjustment

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Abstract

We develop a dynamic model of a fishery which simultaneously incorporates random stock growth and costly capital adjustment. Numerical techniques are used to solve for the resource-rent-maximizing harvest and capital investment policies. Capital rigidities bring diminishing marginal returns to the current period harvest, and introduce an incentive to smooth the catch over time. With density-dependent stock growth, however, catch smoothing increases stock variability resulting in reduced average yields. The optimal management policy balances the catch smoothing benefits against yield loss. We calibrate the model to the Alaskan pacific halibut fishery to demonstrate the main insights.

JEL classification: Q2; D2

Keywords: Stochastic growth; Costly capital adjustment; Pacific halibut fishery

1. Introduction

It has long been recognized that stochastic stock growth and rigidities imposed by quasi-fixed harvesting capital (e.g., fishing fleets) are important elements of the fisheries management problem [23]. Researchers to date however have been unable to jointly incorporate these two fundamental features in the analysis of fisheries management. Computational difficulties have forced authors to either ignore fishing capital constraints altogether or resort to ad hoc assumptions for stock dynamics and harvest technologies [3,4].[1] As a result, little is known about the combined effects of capital constraints and stock growth uncertainty on optimal fisheries management policies.

This paper builds a dynamic model of fishery management that incorporates uncertainty regarding the growth of the biomass and capital adjustment costs. We solve a social planner's problem, to maximize the expected value of the fishery resource by simultaneously choosing the harvest quantity and investment

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[1]Studies that incorporate quasi-fixed harvesting capital typically assume that stock growth is deterministic (e.g., [2,5,26,27]). Models incorporating stochastic stock growth typically ignore harvesting capital constraints (e.g., [1,6,9,23–25]).

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(or divestment) in fish harvesting capital. The resulting dynamic programming problem is solved by Value Function Iteration to obtain the optimal harvest and capital investment feedback policies.

In our framework, the resource manager has an incentive to smooth the catch over time, and most rapid approach path harvesting policies are ruled out. To see why, suppose that favorable growing conditions lead to a large unanticipated increase in the size of the fish stock. The fishery manager could choose to harvest the entire surplus immediately with the currently available fishing fleet. However, this strategy may require large catches per boat, and with diminishing marginal productivity of fishing capital, high harvest costs. The net return from harvesting the surplus fish immediately may be small, particularly if the current fleet size is small. An alternative strategy is to *bank* some of the surplus growth for future harvest. This can allow time to invest in additional fishing capital, which can then harvest the surplus stock at lower cost, and higher net return.

Costly capital adjustment, and more generally, diminishing marginal returns to the current period harvest, creates an incentive to smooth the catch over time. Catch smoothing gains must be traded against the losses that result under widely fluctuating in situ stock abundance [23,24]. A fundamental property of renewable natural resources is that stock growth is density dependent: growth is low when habitat is under-utilized and declines when stock size is large as competition for food and habitat intensifies. Formally, by Jensen's inequality, average growth and correspondingly average sustainable harvest will be highest when the fish stock is stabilized at intermediate levels.

Under stochastic growth the manager must strike a balance between stability of the in situ fish stock and stability of the per-period harvest. Our model balances this trade-off, and shows how the optimal level of catch smoothing is affected particularly by capital adjustments costs, the curvature of the net harvest benefit function, the curvature of the stock growth function, and persistence of environmental shocks.

In addition to the catch smoothing forces, our results highlight the importance of *jointly* determining harvest and fishing capital investment policies. In our model, the immediate harvest value of the fish stock is greater when there are more boats available to catch fish. The optimal current period harvest is an increasing function of the vessel capital stock. Moreover, high capital adjustment costs suggest reduced harvest variability; when it is more costly to move boats in and out of the fishery, it will pay to reduce the variability of the harvest even though this will reduce expected yields over time.

These results have important policy implications. In practice, fisheries management is decentralized: government agencies maintain responsibility for determining harvest policies, whereas private industry invests in fishing capital and carries out harvesting operations. The harvest policy that is chosen by the government agent determines the current and future distribution of catch and stock abundance, and thus determines the return to capital that is vested in a fishery. Managers who ignore the capital investment incentives associated with a particular harvesting rule may inadvertently, and possibly significantly, reduce the value of a fishery resource. Likewise, harvest policies that are insensitive to the size of the vessel capital stock will lower fishery value.

We calibrate our model to Management Unit 3A of the Alaskan pacific halibut (*hippoglossus stenolepis*) fishery. Calibration to an actual fishery demonstrates the importance of the catch smoothing incentive, and the influence of private capital investment on harvesting rules, under realistic conditions. Our results find that the actual management policy in place in the US pacific halibut fishery departs from the optimal policy along two dimensions. First, the halibut stock is managed by setting the yearly harvest as a fixed fraction of the exploitable biomass. Based on our calibration we find that this *constant harvest rate* rule over-smooths the catch relative to the optimal policy. Results indicate that losses attributed to using the constant harvest rate rule range between 1% and 2% of the fishery value.

The second departure from the optimal policy concerns private investment in fishing capital. Although the Alaskan halibut fishery has been managed with individual fishing quotas since 1995, quota trading is severely restricted.[2] These restrictions limit the quantity of halibut that individual vessels are permitted to catch, which effectively places a lower bound on the number of active vessels in the halibut fleet. We find that a much

[2]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-dependent western Alaskan communities, led them to place tight restriction on harvest permit trading. See [8,12,22] for details.

smaller fleet consisting of vessels that target halibut throughout the entire fishing season would reduce average harvesting costs and increase fishery value by as much as 13–19%. The analysis also shows how the harvest policy can be adjusted to maximize fishery value in the presence of its current oversized fishing fleet.

The remainder of the paper is organized as follows. Section 2 presents the model and numerical method used to solve for the optimal policy functions. The structure of the policy functions, and implications for fisheries management are examined in Section 3. Section 4 characterizes the differences between the optimal policy and the actual management policy used currently in the Alaskan pacific halibut fishery. Section 5 summarizes the main findings and provides concluding remarks.

2. The model

We consider a planner who jointly chooses both the per-period harvest and the amount of fish harvesting capital, i.e., size of the fishing fleet, with the goal of maximizing the value of the fishery.[3] Let $t = 1, 2, \ldots$ 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.[4] Period $t+1$ escapement—the quantity of fish that escapes harvest in the current period is $s_{t+1} = x_t - h_t$, where $h_t \in [0, x_t]$ is period t harvest. Escapement is non-negative and cannot exceed the available biomass; $s_{t+1} \in [0, x_t]$.

Fish stock growth is density dependent, and is influenced by random growth conditions in the ocean environment. Following Reed [24] and others, we assume that growth shocks enter multiplicatively;

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

where $G(.)$ is the deterministic component of growth satisfying $\partial^2 G(.)/\partial s^2 < 0$, and z_t is a mean 1 random variable with finite support $[\underline{z}, \overline{z}]$, with $0 < \underline{z} < \overline{z} < \infty$. The random component, z_t, is assumed to be a Markov process with a known transition distribution. Growth shocks may be serially correlated, in which case, the conditional distribution of the $t+1$ period shock will depend on z_t. Identically and independently distributed shocks are a special case.

The stock growth model implies an intermediate level of abundance at which the expected per-period net growth is maximized. Density-dependent growth introduces a trade-off between harvest smoothing and expected yield over time since a reduction in the variation of escapement, $s_{t+1} = x_t - h_t$, implies wider fluctuations in the harvest. The planner could choose to set $s_t = s$ for all t, in which case all growth stochasticity would have to be absorbed by the harvest. Alternatively, the planner could choose a constant harvest $h_t = h$, for all t in which case all growth stochasticity emanates as in situ stock variability. An optimal balance that is struck will depend on the nature of the per-period benefits from fish harvest and capital adjustment costs, which we address next.

The harvest benefit is $B(h_t)$, where $B(.)$ is assumed to be a concave function. The harvest technology utilizes a single capital input denoted by k. For concreteness, k_t will represent the number of vessels in the harvest fleet in period t. Individual vessel harvesting costs are assumed increasing and strictly convex in catch, and non-increasing in the stock abundance. Fleet-level harvesting costs in period t are denoted by $C(h_t, k_t, x_t)$. 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.

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 new capital investment is operational, and before vested capital can be removed. The productive capital stock in period $t+1$ is equal to the depreciated period t

[3]Four US fisheries are managed using individual fishing quotas, which establish property rights to harvest share of the total catch. If quota trading occurs in competitive and frictionless markets, the vessel 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.

[4]While common in the literature, e.g., [24], 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 realization of random stock growth is somewhat representative of the actual timing of events in the halibut fishery, where fisheries scientists at the International Pacific Halibut Commission derive a Bayesian updated estimate of x_t prior to the selection of h_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 are specific assets and are assumed to have discretely lower value in alternative uses in the economy.[5] Even if a vessel can be employed in other fisheries, 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.[6] Specificity of physical and human fishing capital is appropriately modelled as non-convex capital adjustment costs. Denote the capital *purchase* and *resale* prices as p_k^+ and p_k^-, respectively, where $p_k^+ \geqslant p_k^-$.

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:

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

where E_0 is the expectations operator conditional on currently available information, β is the discount factor, and p_k follows:

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

It is instructive to review the timing of decisions and the information available when decisions are made. At the beginning of period t the manager observes the exploitable biomass x_t, the current number of boats k_t and chooses current harvest and investment. Since past escapement s_t is known, the current period shock z_t is also known.[7] As past escapement and current shock jointly determine the exploitable biomass, both s_t and z_t are state variables in the model. Note that, except for the special case of independent shocks, the current shock z_t also conditions the distribution of future shocks. State variables are thus (k_t, s_t, z_t), where k_t and s_t are endogenous, chosen in period $t-1$, and z_t is exogenously determined. Given x_t and k_t, choosing h_t and i_t is equivalent to choosing s_{t+1} and k_{t+1}. Adopting standard dynamic programming literature notation we write the state variables as $(k_t, s_t, z_t) \equiv (k, s, z)$ and the controls as $(k_{t+1}, s_{t+1}) \equiv (k', s')$. It will be convenient to write the current period net harvest benefits as

$$\Pi(k, s, z, s') = B(zG(s) - s') - C(zG(s) - s', k, zG(s)),$$

where we have made the substitution $h = zG(s) - s'$. The management problem can be formulated as a recursive problem with Bellman equation given by

$$V(k, s, z) = \max_{k', s'} \{\Pi(k, s, z, s') - p_k(k' - (1-\delta)k) + \beta E[V(k', s', z')|z]\}, \tag{3}$$

where $E[.|z]$ denotes the conditional expectation given the current shock z, and $V(k', s', z')$ is the optimized value of the fishery given the one-period-ahead state variables. The solution we seek is pair of policy functions $s' = S(k, s, z)$ and $k' = K(k, s, z)$ which determine the controls k' and s' for all possible (current) states (k, s, z). Solutions for $V(.)$, $S(.)$ and $K(.)$ must be approximated using numerical methods. Before we turn to the numerical analysis, several useful insights are obtained by examining the necessary conditions for the solution.

We will consider a special case of the model where the vessel capital purchase and resale prices are equal; $p_k^+ = p_k^- = p$. Under this assumption investment can be reversed at no cost. However, because one period

[5] Clark et al. [5], Matulich et al. [18], and Weninger and McConnell [31] have emphasized the specificity of fishing capital.

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

[7] In the pacific halibut fishery the growth of the stock is affected by surface water temperatures that follow decadal oscillations [7]. Water temperatures are easily measured and thus the assumption of observable shocks is not unreasonable.

delay is required to install and remove capital, investment and divestment must still be forward looking. We will use subscripts to denote partial differentiation.

The first-order conditions and the envelope conditions can be combined to obtain the following optimality condition for the choice of capital[8]:

$$p(r+\delta) = E\{-C_k(h', k', x')|z\}, \tag{4}$$

where r is the interest rate and we have used the relation $\beta \equiv 1/(1+r)$. The left-hand side of (4) is the real rental price of a unit of vessel capital while the right-hand site denotes the expected reduction in marginal harvesting cost (assuming $C_k < 0$) from adding the marginal unit. Under general harvesting technologies, the expected cost reduction from adding capital will vary with next-period harvest $h' = z'G(s') - s''$ and next periods stock, $x' = z'G(s')$. In general, we expect $C_{kh} \neq 0$, and $C_{kx} \neq 0$ which implies that the expected cost saving from adjusting capital is affected by the escapement choice s'. Hence, capital k' and escapement s' choices cannot be made independently.

Following similar steps as above yields the Euler equation for escapement, and thus harvest,

$$\Pi_h = \beta E\{(\Pi'_h + \Pi'_x)z'G_s(s')|z\}, \tag{5}$$

where Π' denotes the one-period-ahead net harvest benefits (function arguments have been dropped to ease notation). Eq. (5) is a modified golden rule for our model: the left-hand side is the marginal net benefit from harvesting an additional unit of the fish stock in the current period, while the right-hand side is the shadow price of the resource, i.e., the discounted expected value of a marginal unit of stock in situ. Leaving a unit of the stock in the ocean for another period adds $z'G_s(s')$ units to next-period stock. The value of this marginal growth is the marginal contribution to future net harvest benefits Π'_h plus the marginal reduction in harvesting costs, or *stock effect*, $\Pi'_x = -C'_x$ (>0). From (5) we see that the current marginal value of harvesting a unit of the fish stock is set equal to the discounted expected (total) gain from leaving that unit in the sea. Note also that Π'_h and Π'_x both depend on the one-period-ahead fleet size, suggesting, as above, that current escapement s' must be chosen jointly with k'.

When net harvest benefits are concave in h, variations in stock abundance caused by random growth shocks are spread over time in order to satisfy (5). Suppose for a moment that there is no harvesting cost stock effect, $C_x = 0$. The Euler equation in (5) becomes $\Pi_h = \beta E\{\Pi'_h z' G_s(s')|z\}$. In a deterministic environment the steady-state harvest will satisfy $\Pi_h = \Pi'_h$ which suggests $z'G_s(s') = \beta^{-1}$; in steady state the gross growth rate equals the gross interest rate. In the stochastic environment of our model, both h and s' have uni-modal stationary distributions. Notice that $G_s(s')$ is known; then ignoring the covariance between Π'_h and z', assume for a moment that $\beta E\{z'G_s(s')|z\}$ is close to unity.[9] We see that optimal escapement is chosen to equate the current and the one-period-ahead expected marginal net benefit; $\Pi_h = E\{\Pi'_h\}$. The net benefit function is strictly concave, $\Pi_{hh} < 0$. Satisfying Eq. (5), by Jensen's inequality, requires smoothing the harvest over time.

Catch smoothing benefits must however be balanced against stock smoothing forces. Suppose a sudden windfall in stock abundance, x is realized. One strategy is to set s' such that current harvest $h = x - s'$ satisfies $\Pi_h = E\{\Pi'_h|z\}$. However, if x is large, this strategy may require that s' is too large. Concavity of the stock growth function implies that $G_s(s')E\{z'|z\}$ may be small relative to β^{-1} when s' is large.

The curvature of the stock growth function and the curvature of the net benefit function, more precisely the magnitudes of G_{ss} and $\Pi_{hh} = B_{hh} - C_{hh}$, will determine how much catch smoothing is carried out under the optimal management policy. Stock growth and the benefits from consuming fish, $B(.)$ are exogenous to the model. However, because marginal harvesting cost is affected by fleet size, the curvature of the harvest cost

[8]First-order conditions for the capital and escapement choice are, $-p + \beta E\{V_k(k', s', z')|z\} = 0$, and $-B_h + C_h + \beta E\{V_s(k', s', z')|z\} = 0$, respectively. Envelope conditions for capital and escapement are, respectively, $V_k(k, s, z) = -C_k + p(1-\delta)$ and $V_s(k, s, z) = (B_h - C_h - C_x)zG_s(s)$.

[9]Note that

$$\beta E\{\Pi'_h z' G_s(s')|z\} = E\{\Pi'_h\}\beta G_s(s')E\{z'|z\} + G_s(s')Cov\{\Pi'_h, z'\}.$$

In general, a higher value of z is expected to call for a higher value of h and thus the covariance term is likely to be negative. However, under the presence of diminishing marginal return, as the harvest variability is muted, the magnitude of the covariance is relatively small and can be safely ignored for the sake of exposition.

function is endogenous to the model. Put simply, adding another boat to the fleet means that each vessel harvests a smaller share of h. Under our assumption that vessel-level costs are increasing and strictly convex in catch, $C_{hk}<0$ in the effective region, the manager can affect the rate at which future harvesting costs increase.

Consider once again the case of a sudden windfall of stock abundance. Since curvature of the current net benefits cannot instantaneously be adjusted, it may pay to rent another boat (with reversible investment, renting and buying are equivalent) and wait to harvest some of the excess stock next period. Delaying harvest, or banking some of the excess growth, provides time to increase k' and reduce the concavity of the one-period-ahead net benefit function. At the margin, this capital adjustment must follow (4).

Lastly, notice that the conditional expectations for the future shock affects the necessary conditions for both capital investment and escapement. Costello et al. [9] study the effects of expected growth productivity shocks on escapement. These authors find that when future stock growth conditions are expected to be good, more fish should be left in the sea since the expected return to investing in the in situ fish stock is relatively high. This result leads to a somewhat counter-intuitive harvest policy where, ceteris paribus, current catch is reduced (increased) if future environmental conditions and future stock abundance is expected to be high (low). Eq. (5) shows as well that the incentive to invest in the fish stock is enhanced when expected environmental conditions are above average. Importantly, however, because our model assumes that net harvest benefits are a concave function of the catch, an important counterforce to the incentives outlined in Costello et al. [9] is present. Suppose the manager expects that poor stock growth conditions will prevail in the future. Reducing current escapement in anticipation of poor stock growth means increasing current period harvest. But since $\Pi_{hh}<0$, a high h would mean low-marginal net harvest benefits currently. With low escapement and poor anticipated growth, the manager would also expect to be *starved* for fish in the next harvest period, which would cause $E\{\Pi'_h|z\}$ to be high. It is easy to see that the incentive to smooth the harvest over time counteracts the incentive to adjust the investment in the in situ stock in response to changes in anticipated stock growth conditions. Indeed, if the catch smoothing incentive is sufficiently strong, the optimal harvest can vary positively with anticipated stock growth conditions.

With costly investment reversibility, $p_k^+>p_k^-$, the forces underlying the capital and escapement Euler equations remain operational, although capital adjustments will be muted. New investment will be undertaken when the current realization of growth shock is particularly high. Conversely, existing vessel capital will be put on sale when the current shock realization is particularly low. For the intermediate range of shocks it will be optimal, however, to neither invest in new capital nor sell the existing stock. These investment responses will also depend on the current size of the stock biomass and persistence of shocks.

Numerical solutions for $V(.)$, $S(.)$ and $K(.)$ are needed to generate further insights, and the next section numerically solves the model calibrated to a particular fishery. It should be emphasized that the forces that underlie the catch smoothing incentive outlined in this section will be present except in very special circumstances. From Eq. (5) we see that the harvest smoothing incentive disappears if $\Pi_{hh}=0$. The required condition is that net harvest benefits be linear in h. For this condition to hold in practice requires first that the marginal benefit of consuming fish is constant (non-diminishing). If consumer surplus plus producer revenue is adopted as a benefit measure, $B_{hh}=0$ only if the demand for fish is perfectly elastic. Perfectly elastic fish demand may be a reasonable assumption for some fisheries if for example consumers view different species of fish as substitutes and the harvest from the fishery under consideration is small relative to total fish production. A second requirement is that $C_{hh}=0$, in other words, the marginal cost of harvesting fish is constant. Constant marginal harvesting cost requires that the returns to a fixed vessel capital stock do not diminish, or fishing capital can be costlessly and instantaneously adjusted. These conditions are not representative of real world fisheries.

In sum, the assumption of diminishing marginal returns to the current period harvest quantity would appear to be quite robust. Thus, while optimal management policies will differ quantitatively across fisheries, qualitatively, the principles discussed in this section and the qualitative results to follow generalize to other fisheries.

2.1. Value function iteration

We solve for $V(.)$, $S(.)$ and $K(.)$ numerically by iterating on the Bellman equation (3). Judd [17] provides a complete discussion of Value Function Iteration.

The numerical technique entails discretizing the state space and then iterating on the Bellman equation, starting with an initial guess V_0 for the value function. It can be shown (see [28]) that the iterative process converges to the unique value function V. 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.

The Bellman equation for the optimization problem can be rewritten as

$$V(k,s,z) = \max_{k',s'} \{F(k,s,z,k',s') + \beta E[V(k',s',z')|z]\},$$

where $F(k,s,z,k',s') \equiv \Pi(k,s,z,s') - p_k(k' - (1-\delta)k)$ denotes the net harvest benefits less any capital adjustment costs or receipts given current states (k, s, z) and next period's endogenous states k' and s'. We discretize the state space in the following way. First, the stochastic process for z is approximated by n^z states, $\{z_1, z_2, \ldots, z_{n^z}\}$, characterized by a transition probability matrix P with dimension $n^z \times n^z$. Further, let n^k and n^s be the discrete number of states for the number of boats and escapement, given by $\{k_1, k_2, \ldots, k_{n^k}\}$ and $\{s_1, s_2, \ldots, s_{n^s}\}$, respectively. Then, we can represent V defined over a three-dimensional discrete space with dimensions $n^k \times n^s \times n^z$. Define an operator TV that maps the function V to another function over the same space. The unique fixed point of this mapping is obtained as $V = TV$. The elements of TV are obtained as follows:

$$TV(k_l, s_m, z_i) = \max \left\{ \underbrace{F_{lmi}}_{n^k \times n^s} + \underbrace{\beta \sum_{j=1}^{n^z} P(i,j) \underbrace{V(.,.,z_j)}_{n^k \times n^s}}_{n^k \times n^s} \right\}, \tag{6}$$

where F_{lmi} is an $n^k \times n^s$ matrix whose element in the vth row and wth column is defined as $F_{lmi}(v,w) \equiv F(k_l, s_m, z_i, k_v, s_w)$. Note that $P(i,j) \equiv \Pr(z' = z_j | z = z_i)$ is the $\{i,j\}$ element of the transition matrix. Within brackets, the two $n^k \times n^s$ matrices are first added element by element, and then the max operator returns the maximum element of the resultant matrix. We begin with an initial guess for V as V_0. Then, $V_{n+1} = TV_n$. In this manner, we iterate until convergence is achieved as per our criterion of $\max\{|V - TV|\} < 0.0001$. Notice that (6) also obtains policy functions for the choice of number of boats and escapement for the next period. Specifically:

$$k' = K(k_l, s_m, z_i) = k_{\text{row}}$$

and

$$s' = S(k_l, s_m, z_i) = s_{\text{col}},$$

where row and col refer to the row and column of the maximum element on the right-hand side of (6).

2.2. Calibration to the Alaskan halibut fishery

We calibrate the model to the Alaskan pacific halibut fishery. Halibut are a long-lived bottom dwelling flatfish species which exhibit relatively slow intrinsic rates of growth. Stock abundance and growth is relatively well-understood (see [29]). Growth and survival rates vary with changing ocean water temperatures, currents, availability of food among other factors. Growth rates are positively correlated with ocean current patterns that are persistent, following multiple-year cycles.

Halibut are harvested with longline gear, i.e., baited hooks spaced along a main cable that is lowered to the sea floor. After the gear has soaked, the longline is recovered with a hydraulic winch. Captured fish are placed on ice and transported to ports in Alaska and Seattle. Most halibut is sold in fresh form to US restaurants and grocery stores. Alaskan halibut revenues exceeded \$172 million in 2003.

The model consists of four components: (1) the harvest benefit function; (2) the fleet harvesting cost function; (3) capital purchase and sale prices; and (4) the stock growth function. Due to space limitations, we present a brief overview of the calibration of each component. A complete discussion of the data and

Table 1
Model calibration summary

Component	Functional form	Base case parameters
Harvest benefits	$B(h) = \alpha_1 h - \frac{1}{2}\alpha_2 h^2$	$\alpha_1 = 2.9854;\ \alpha_2 = 3.6 \times 10^{-4}$
Fleet costs	$C(h,k,x) = k \cdot c(q,x),\ q = h/k$	$FC = 134.451;\ \beta_0 = 0.453;$
Vessel costs	$c(q,x) = FC + (\sum_{j=0}^{3} \beta_j q^j)x^{-\beta_x}$	$\beta_1 = 0.130; \beta_2 = -0.387 \times 10^{-3};$ $\beta_3 = 0.750 \times 10^{-6};\ \beta_x = 1.0281$
Capital price	$p_k = \begin{cases} p_k^+ & \text{if } k' > (1-\delta)k \\ p_k^- & \text{if } k' \leqslant (1-\delta)k \end{cases}$	$p_k^+ = \$236,500;\ p_k^- = \$160,000$ $\delta = 0.1$
Stock growth	$G(s) = s + \gamma s(1 - s/x^c)$	$\gamma = 0.283;\ x^c = 443,392.07$

estimation used to calibrate the model is presented in an extended appendix, which is available from the authors.

Harvest benefit function: Following Criddle and Herrmann [10], we assume a linear inverse demand for halibut, $D^{-1}(h) = \alpha_0 - \alpha_1 h$. Using consumer surplus as a measure of consumer welfare, the per-period total benefit from the halibut harvest h is the sum of consumer surplus plus industry revenues

$$B(h) = \alpha_1 h - \tfrac{1}{2}\alpha_2 h^2, \tag{7}$$

where benefits are denoted in 1997 dollars (all subsequent values are also in 1997 dollars). All parameter values are reported in Table 1.

Harvesting costs: Operating cost data from a sample of 69 class 2 vessels that harvested halibut during the 1997 fishing season are used to estimate fleet harvesting costs. Variable costs include fuel, bait and ice, and food and supplies for the captain and crew, and lost gear. A cubic functional form is used to allow a flexible relationship between vessel harvest costs $c(q,x)$ and catch q

$$c(q,x) = FC + (\beta_0 + \beta_1 q + \beta_2 q^2 + \beta_3 q^3)x^{-\beta_x}, \tag{8}$$

where FC denotes annual fixed costs, e.g., expenses for vessel mooring and storage, permits and licence fees, and fees for accountants, lawyers, office support, and routine maintenance and repairs.[10]

Capital adjustment costs: We assume that a well-functioning market exists for used fishing boats and set the capital salvage price, p_k^- equal to the mean self-reported resale value from the 1997 cost data. The wedge between the purchase and resale price is assumed to result from refitting costs that are incurred when switching between fisheries. 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. 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. Our baseline calibration assumes the wedge between the vessel purchase and resale prices is equal to the refit cost of \$76,500. Capital depreciation, δ, is the mean value reported in the 1997 data.

Stock growth model: We obtained pre-harvest exploitable biomass, x, harvest, h and escapement, s, data for Management Unit 3A during 1974–2003. A logistic growth function, $G(s) = s + \gamma s(1 - s/x^c)$, is fit to the data using an iterative feasible generalized least-squares procedure. The state space for the random shock z and the Markov transition matrix are calculated following [17, pp. 85–88].

Table 1 summarizes the calibration and reports baseline parameter values. We emphasize that data limitations required that the model be calibrated to Management Unit 3A only. This management unit produces roughly 55% of all commercial harvests (US and Canada). Differences in stock growth throughout

[10]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, and crew adjustments tend to be infrequent.

the halibut range, and differences on harvesting costs, do not allow us to extrapolate the results to the entire halibut fishery (which extends through the Bering Sea and Gulf of Alaska along the North American pacific coast to California). We have also assumed that the fishing fleet is comprised entirely of class 2 vessels, i.e., vessels ranging in length from 35 to 60 ft. This is the most common vessel size, and class 2 vessels harvest the largest share of the Alaskan catch (on average 54.92% during 1995–2002). Lastly, growth shocks are positively serially correlated due to cyclical weather patterns that impact water temperature and stock growth.

The empirical calibration is subject to the usual econometric limitations, e.g., specification and data errors. The results that follow must be interpreted with these limitations in mind.

3. Results

3.1. The optimal policy

Fig. 1 plots a cross section of the optimal escapement policy function $s' = S(k, s, z)$. The range of the k and s values correspond to their respective 99% confidence intervals obtained from the invariant distributions, and the value of the shock, z, is equal to its mean of 1.

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 beginning period stock size x is also relatively large. With costly capital adjustment, particularly in the short run, and diminishing marginal net benefits, it is best to increase the current escapement and *bank* some fish for future harvest.

With a large fishing fleet, the costs per unit of harvested fish rise at a slower rate. Alternatively, the rate at which current period marginal net benefits decline is less when k is large. As shown in Fig. 1, optimal escapement (current period harvest) is inversely (directly) related to the size of the fishing fleet.

Note that with serially correlated shocks, a different cross section of the escapement policy exist for each realization of z. These results are qualitatively similar to those reported in Fig. 1 and to save space are not reported.

The capital investment policy function is more complicated. Fig. 2 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 (204 million pounds). Panel (b) depicts optimal k' conditional the previous escapement, s, this time holding k constant at its median value of 58 boats. Both panels report results for the mean value shock, $z = 1$.

The marginal value of fishing capital depends on current and future harvest and stock abundance, and includes the value of the option to optimally respond to changes is stock conditions over time. Fig. 2 shows that prescribed changes in the fleet size are quite intuitive.

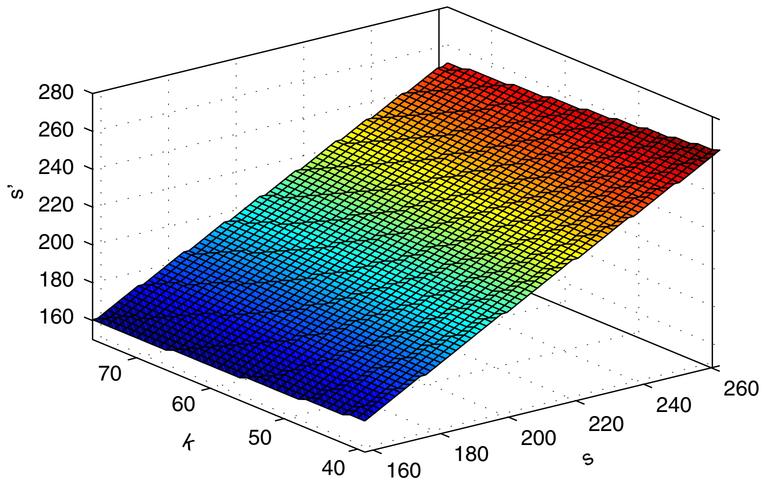

Fig. 1. Optimal escapement policy.

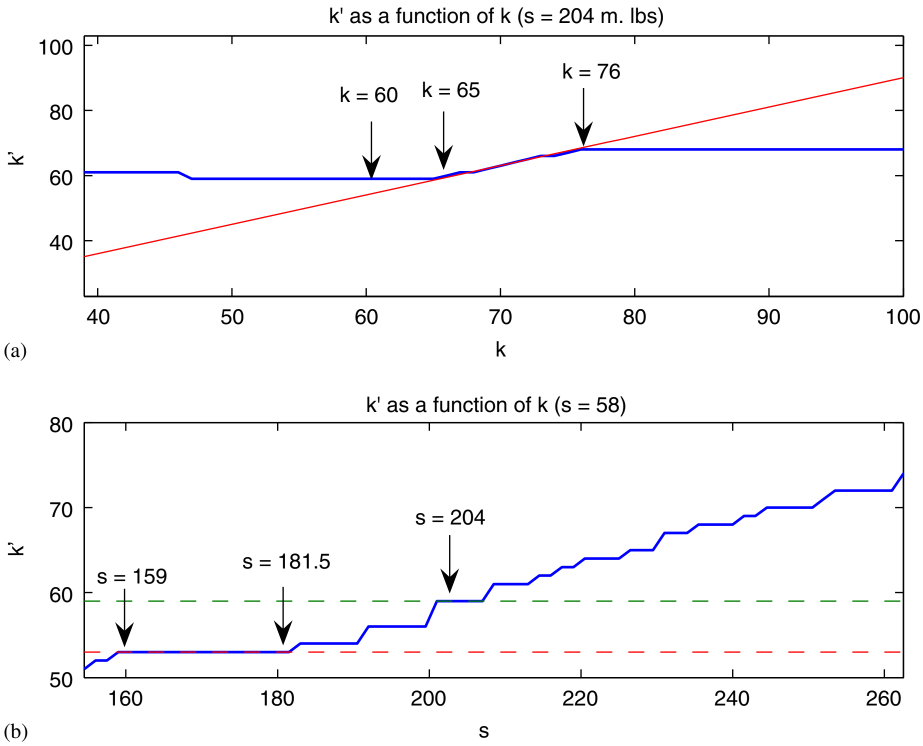

Fig. 2. Optimal capital investment policy.

Consider panel (a) in Fig. 2 first. Recall that as the current fleet size increases, moving left to right in the figure, escapement declines (see Fig. 1). Consequently, future expected harvest declines with larger k which implies that the expected marginal value of capital declines with k. The number of boats that are *added* to the fleet declines in k for k between 40 and 50 boats.

To assist in interpreting the results, a dashed line identifying zero net investment, $k' = (1-\delta)k$, is shown in panel (a). 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 60 and 65 boats, boats are being added to the fleet however at a rate that is less than physical depreciation. For fleet sizes between roughly 65 and 76 boats, 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 fleet. At $k \geqslant 76$, divestment is optimal since the expected marginal value the current capital stock is below the salvage price p_k^-.

Turn now to panel (b) in Fig. 2. To assist in interpreting the results, a dashed line has been drawn at current fleet size, $k = 58$ boats, and at $(1-\delta)k$ equal to 53 boats. At escapement levels below 159 million pounds, future expected catch is low and the expected marginal value of capital, adjusted 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 159 and 181.5 million pounds, the expected marginal value of capital (at $k = 58$) lies between the capital salvage and purchase prices. As in panel (a), investment inactivity is prescribed. At $s = 181.5$ million pounds, boats are added but at a rate less than depreciation; the expected marginal value of *effective* capital is maintained at p_k^+. At $s = 204$ million pounds and above, the expected marginal value of capital exceeds p_k^+ and net investment is positive.

Turn now to the role of the environmental shocks. Our investigations of the policy functions find that the optimal escapement and capital investment choices vary with z in expected ways. We can obtain further insights by isolating the effects of good versus poor expected environmental conditions. For this purpose the following experiment was conducted. In a separate simulation we solved for the optimal escapement policy under the assumption that net benefits are *linear* in the harvest. Essentially, we remove the catch smoothing incentive capital from the model by assuming that marginal harvesting costs are constant and that consumer demand for halibut is perfectly elastic.

We then hold recruitment x fixed and examine how the optimal escapement choice varies with z. The scenario under consideration is thus one where the manager finds herself with the same beginning period stock abundance but has different expectations about the distribution of the future growth shock.[11]

Results for the case where $\Pi_{hh} = 0$ find that optimal escapement varies positively with z. Recall that growth shocks are positive serially correlated. When the current z is low, the manager also expects poor environmental conditions to prevail one period ahead, and correspondingly leaves fewer fish in the sea because the expected return on investments in the fish stock is relatively low [9]. When the current z is high, good expected growth is expected and escapement is higher.

We compare these results to the optimal escapement policy under our baseline calibration with $\Pi_{hh} < 0$. We find that the optimal escapement is pretty much flat irrespective of the value of z. Thus, the Costello et al. prediction that a higher z should imply a higher s' does not hold due to the catch smoothing incentive in our model.

The results from this experiment also find that, in anticipation of high stock abundance in the future, the size of the fishing fleet is increased, with more vessels being added the higher is the current period environmental shock. By adding more boats, the manager reduces the rate at which future marginal harvesting costs increase (the rate that future marginal net benefits decline). This investment is made in anticipation of the larger expected stock size and harvests in future periods.

Further insights are obtained by examining the effects of model parameters on the invariant distributions of control and state variables. 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. Columns 2–5 of Table 2 report results under alternate model parameterizations which are chosen to demonstrate the intuition.

Column 2 of Table 2 reports results under the higher capital purchase price, and increased adjustment costs.[12] When boats are more expensive average fleet size is reduced and when capital adjustment is more costly less adjustment in the fleet size occurs, as indicated by the confidence interval for the fleet size.[13]

Notice also the increase in the value and the volatility of escapement in column 2. When it is more costly to adjust the size of the fleet, it is also more costly to adjust the size of the in situ stock, e.g., large adjustments to the harvest may require costly changes in fleet size. The increase in vessel capital costs reduces the overall economic flexibility, and the manager reduces the volatility of the catch to some degree, which implies volatility of escapement rises. Consumer surplus changes very little under the higher capital costs. As expected, industry profits are considerably less and more variable than in the baseline calibration.

Column 3 of Table 2 reports results under a lower discount factor, a higher interest rate. A higher interest rate changes the model variables in expected ways: escapement is reduced (harvest is increased) so that the expected return on investment in the in situ stock is equal to the now higher interest rate. The real price of capital has increased and slightly fewer boats are employed in the fishery on average. Consumer surplus and industry profits are smaller due primarily to the higher discounting of future returns.

Column 4 of Table 2 reports results for the case where the fishery is managed in order to maximize the present discounted value of industry profits, rather than total net benefits (industry profit plus consumer surplus). The harvest benefit function in this case is more concave than in the baseline calibration because marginal industry revenues decline more sharply than marginal total benefits. A key effect is an increase in the

[11] In our model, there are n^z possible ways to arrive at the same (approximate) level of recruitment. For example, a given x is obtained with a high past escapement and low shock, or a low past escapement and a high shock. Notice that this experiment replicates the conditions considered in [9] and thus we confirm their result.

[12] Halibut skippers indicate 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. In column 2, $p_k^+ = \$800,000$ and $p_k^- = \$25,000$. (The base case capital prices are $p_k^+ = \$236,500$ and $p_k^- = \$160,000$.)

[13] The reader will note that relative to the baseline calibration, the standard deviation for the number of boats is higher with increased capital adjustment costs. Closer examination revealed that the standard deviation is misleading due to large differences in the distribution kurtosis. The tighter confidence interval for the fleet size under the higher capital adjustment costs more accurately describes capital adjustments.

Table 2
Sensitivity analysis

	Baseline calibration	High capital cost	High discount factor	Max. indus. profits	iid shocks
Capital	57.78[a]	53.02	57.05	54.84	58.63
(boats)	(4.44)[b]	(6.51)	(7.43)	(2.25)	(4.91)
	[39, 76][c]	[36, 67]	[38, 74]	[45, 56]	[46, 69]
Escapement	204.61	209.11	165.27	247.24	204.69
(mill. lbs.)	(20.78)	(21.92)	(18.41)	(39.81)	(14.85)
	[157.5, 262.5]	[159.0, 270.0]	[124.0, 217.0]	[160.0, 356.5]	[170.5, 244.0]
Harvest	31.11	31.17	29.29	30.20	31.01
(mill. lbs.)	(4.96)	(4.87)	(4.81)	(2.38)	(3.35)
	[19.16, 43.57]	[19.20, 43.30]	[17.87, 41.86]	[22.23, 34.54]	[22.26, 39.78]
Harvest rate	13.13	12.91	14.99	11.01	13.14
(%)	(0.77)	(0.71)	(0.82)	(0.84)	(0.51)
	[10.59, 14.48]	[10.51, 14.15]	[12.26, 16.46]	[8.73, 12.56]	[11.52, 14.19]
Catch/boat	527.31	585.72	511.45	549.90	528.62
(thous. lbs.)	(27.16)	(28.84)	(24.79)	(25.09)	(23.83)
	[451.63, 592.15]	[505.16, 656.30]	[442.35, 573.88]	[475.96, 608.14]	[460.64, 588.04]
Indus. profit	41.60	38.54	39.87	42.91	42.04
($ mill. 1997)	(2.31)	(3.20)	(2.64)	(1.80)	(1.49)
	[32.78, 44.87]	[28.29, 44.61]	[30.50, 43.77]	[36.28, 45.96]	[36.78, 44.50]
Cons. surplus	17.86	17.91	15.86	16.52	17.38
($ mill. 1997)	(5.62)	(5.52)	(5.16)	(2.51)	(3.77)
	[6.60, 34.17]	[6.63, 33.75]	[5.75, 31.54]	[8.90, 21.48]	[8.92, 28.48]

[a]Denotes mean value.
[b]Denotes standard deviation.
[c]Denotes 99% confidence intervals.

standard deviation of escapement and a reduction in the mean and standard deviation of the harvest. The increased concavity in the current period payoff function induces greater catch smoothing at a cost of increased escapement volatility and lower average yield. Interestingly, when consumer surplus is not valued by the fishery manager, more fish are left in the sea i.e., a more conservative harvest policy is adopted.

Column 5 of Table 2 reports results under iid shocks. The main effect, relative to the base case, is to reduce the variance of most state and control variables, as well as the corresponding welfare measures. Under independent shocks the probability of observing a sequence of low or high shocks is reduced; s and k spend less time in the tails of their respective distributions. This suggests that there will be fewer *adjustments* required to maintain the state variables at preferred levels. In particular, the 99% confidence interval for boats is much tighter under iid shocks. A comparison of the welfare measures under iid shocks and the baseline model indicates that the reduced capital adjustment increases industry profits.

Summarizing the results reported in Table 2 we find that 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.

Finally, we consider the value of the fishery, $V(k, s, z)$, if managed under the optimal policies. Like the policy functions described above, the fishery value depends on the state variables k, s, and z. Our results show that the value function is increasing in the initial 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 ([15,19,14]; see also [21]), 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.[14] Given k and s, a higher (lower) value of z implies a higher (lower) current stock abundance. Moreover, with positively serially correlated shocks, a high current growth shock increases the probability of high future shocks, and visa versa. Fishery value is thus increasing in z. To provide context for our results the value of the optimally managed fishery at the mean values for (k, s, z) is roughly \$1.645 billion.

4. Implications for real world fisheries management

Contrary to our model of a single planner, real world fisheries management programs tend to be decentralized. Government agencies maintain control over harvest policies, whereas private industry carries out investments in fishing capital and harvesting operations. As shown in the preceding section, the harvest policy determines the distribution of total fleet and individual vessel catch over time and thus determines the value of vested fishing capital. This section demonstrates these principles in practice. We briefly discuss the pacific halibut management program. We then demonstrate how differences between the optimal and the actual management policy that is currently in place in the pacific halibut fishery affect fishery value.

4.1. Overview of US pacific halibut management

The International Pacific Halibut Commission (IPHC) is responsible for managing the pacific halibut stock.[15] Following each harvest season (March 15 through November 15), commercial catch and effort data, and when available independent survey data, is analyzed by fisheries scientists at the IPHC. The data are used to generate a Bayesian updated estimate of halibut stock abundance across its range. IPHC scientists make a catch recommendation for the upcoming harvest season. An annual meeting is scheduled prior to the season opening at which time members of the public are invited to comment on the IPHC catch recommendation. 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, 20%, of the estimated exploitable biomass.[16]

Prior to 1995, command and control regulations were used to ensure commercial harvests did not exceed target levels. Restrictions on the length of the fishing season were used to limit the total fleet catch. Because entry of new vessels was unrestricted, fleet size grew unabated, leading to increasingly shorter halibut fishery openings. The *race for fish* that ensued is an often cited example of the failures of command and control management. In 1994, for example, the bulk of the US annual halibut catch was harvested in two 6 hour openings.

Short season lengths, a dangerous race for fish, and economic waste spurred the adoption of a property rights-based management approach in 1991 for the Canadian fleet and in 1995 for the US 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 5484 vessels owners and leaseholders that had verifiable commercial halibut landings during 1988–1990.[17]

Designers of the US rights-based program were concerned that unrestricted transferability of IFQs would lead to significant geographical redistribution of harvesting activity. In particular, it was feared that

[14]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.

[15]A 1923 convention between Canadian and US 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. Crutchfield and Zellner [11] provide a comprehensive account of the historical development of the pacific halibut fishery.

[16]A constant harvest rate policy is suggested for pacific halibut fishery by Sullivan et al. [29], "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".

[17]See Committee to Review Individual fishing Quotas [8] for additional discussion of the operation of the US rights-based management program. Grafton et al. [16] discuss the Canadian rights-based management program.

consolidation of IFQ ownership would change the fishery from a small-boat fishery concentrated in western Alaskan coastal communities to a large boat fleet operating out of non-Alaskan ports, in particular Seattle, Washington. 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 requirement that the IFQ owner be on board the vessel when fishing takes place was imposed, and restrictions were placed on quota transferability from smaller to larger vessels. Finally, a complex system of *blocking* was adopted which effectively limits the quantity that can be harvested from a single vessel (see [22]).

Space limitations do not permit a complete description of the halibut management program or the factors that lead to its design. The reader is referred to an extended appendix to this paper (see also [8,22]).

4.2. Departures from the optimal policy

We characterize the current management regime as exhibiting two main departures from the optimal policy identified in Section 3. First, the fish stock is managed using a constant harvest rate (hereafter, CHR) rule, by which the catch is determined as a fixed percentage of the beginning period stock. In the notation of the model in Section 2, $h = \theta z G(s)$, where $\theta \in [0, 1]$. Under the CHR rule escapement does not vary with fleet size. Harvest is increasing in x, but depends on the product of the growth shock and $G(s)$, whereas under the optimal harvest policy, z and s have separate effects on escapement and thus harvest.

A second obvious difference between the actual and optimal policy results from the restrictions placed on the consolidation of harvest quota; the number of boats in the pacific halibut fishery is bounded below. To analyze the effects of this policy we require an estimate of the regulated minimum fleet size. DiCosimo [12] 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 1050 boats. This estimate cannot be translated directly to our calibration which focusses on Management Unit 3A and class 2 vessels only. We can capture the *intent* of the regulation. The average annual harvest of halibut in Alaska during 1995–2002 was 50.945 million pounds. On average, class 2 boats harvested 55% of this total and numbered 50% of the halibut fleet. The restrictions on quota trading were designed such that class 2 boats harvested on average no more than 53,295 pounds of halibut annually: the minimum number of class 2 vessels is $0.5 \times 1050 = 525$, and the class 2 quota share is $0.5492 \times 50.945 = 27.98$ million pounds. Scaling this intended catch per boat to match the average harvest quantities from Table 2 suggests a regulated minimum fleet size of 583 vessels.

Most halibut vessels spend only a small fraction of the year fishing for halibut and participate in other fisheries during each year. The baseline model discussed in the previous section assumes vessels specialize in halibut for the full 8 month season. Our data indicate that sample vessels spent only 9.4% of their total trips per year fishing for halibut. There are two adjustments we need to make to the model to account for this. First, since each boat spends only a fraction of total trips fishing for halibut, our estimate of the fixed costs associated with operating a boat is too high. We thus scale down the fixed cost of operating a boat so that is in proportion to the fraction of trips spent fishing for halibut. Second, we add refitting costs to the (adjusted) annual fixed costs of operating the boat since each boat must *gear up* for the halibut season each year.

Column 1 of Table 3 repeats the optimal policy results for the baseline calibration. Column 2 reports the results under a CHR rule and the corresponding optimal capital investment policy. That is, conditional on the employing a CHR harvest rule, we solve for the optimal capital investment policy functions. This scenario represents the case where the IPHC continues to select the annual catch following the CHR, and all quota trading restrictions are removed.[18] The results for the harvest rate that maximizes the value of the fishery (13.26%) are reported. (The fishery-value-maximizing harvest rate did not depend strongly on the choice of initial conditions.)

Comparing the results in columns 1 and 2 of Table 3 finds that the mean and the standard deviation of boats is higher under the CHR policy, and that escapement is smaller but more variable under the CHR rule. The lost flexibility for adjusting the harvest rate explains this finding. Under the optimal policy h/x is adjusted in response to random stock growth and changes in fleet size. Under the CHR rule, catch is increased (reduced)

[18] We must also assume frictionless quota trading and a perfectly competitive quota market.

Table 3
Constant harvest policy

	Opt. capital		Fixed capital	
	Opt. harvest	Best CHR	Opt. harvest	Best CHR
Capital	57.78[a]	58.58	583	583
(boats)	(4.44)[b]	(5.57)	(0)	(0)
	[39, 76][c]	[45, 72]	na	na
Escapement	204.61	201.73	199.90	237.74
(mill. lbs.)	(20.78)	(27.24)	(17.12)	(29.17)
	[157.5, 262.5]	[138.0, 274.5]	[161.5, 247.0]	[168.0, 315.0]
Harvest	31.11	30.85	31.05	30.90
(mill. lbs.)	(4.96)	(4.18)	(5.22)	(3.82)
	[19.16, 43.57]	[21.15, 41.84]	[18.66, 44.55]	[21.09, 41.74]
Harvest rate	13.13	13.26	13.35	11.50
(%)	(0.77)	(0)	(1.10)	(0)
	[10.59, 14.48]	na	[10.21, 15.28]	na
Catch/boat	527.31	524.88	53.26	53.98
(thous. lbs.)	(27.16)	(29.20)	(8.95)	(6.54)
	[451.63, 592.15]	[450.62, 599.77]	[32.00, 76.41]	[37.66, 70.36]
Indus. profit	41.60	41.68	14.56	15.67
($ mill. 1997)	(2.31)	(2.04)	(3.83)	(3.04)
	[32.78, 44.87]	[34.59, 44.83]	[14.84, 19.21]	[11.97, 34.34]
Cons. surplus	17.86	17.44	17.84	17.61
($ mill. 1997)	(5.62)	(4.72)	(5.92)	(4.66)
	[6.60, 34.17]	[8.05, 31.51]	[6.26, 35.72]	[6.16, 20.52]

[a]Denotes mean.
[b]Denotes standard deviation.
[c]Denotes 99% confidence intervals.

when stock abundance is large (small), but adjustments to the harvest are less aggressive. The result is a more widely dispersed escapement distribution and lower average biomass yield.

The top panel of Fig. 3 shows the harvest rate under the optimal policy (the optimal harvest rate has been smoothed for presentation purposes) and the CHR rule holding the fleet size at its median value, $k = 58$ and for $z = 1$. The beginning period stock abundance x is shown on the horizontal axis. At low levels of abundance (e.g., $x < 210$ million pounds) the optimal harvest rate is below the CHR. The optimal policy rebuilds the stock more aggressively than does the CHR. At intermediate levels of abundance the optimal harvest rate is close to the CHR, and at biomass levels exceeding 280 million pounds, the optimal harvest rate is below the CHR. Recall that harvesting capital is fixed in the current period. While abundance is high, harvesting large quantities of fish with the current fleet of $k = 58$ boats raises average harvesting costs. It is better to reduce the harvest rate and *bank* some of the excess stock, which can be harvested in future by a larger fleet. The CHR does not allow this level of flexibility to adjust the harvest intertemporally.

The bottom panel of Fig. 3 shows the optimal capital investment and capital investment under the CHR rule. As above, the current fleet size is $k = 58$, $z = 1$, and the horizontal axis shows stock abundance at the beginning of a period. The differences between the two capital investment policies are most pronounced at low and high levels of stock abundance. Notice that for x below 200 million pounds, more vessels are being removed from the fleet under the optimal policy. This is because the manager is aggressively rebuilding the stock and harvest is expected to be low one period ahead. Under the CHR, a higher one-period-ahead harvest is expected and divestment is muted. At high levels of the beginning period stock, the optimal policy is banking fish for future harvest (relative to the CHR). In anticipation of the higher future harvest fleet size is increase by a larger amount than under the CHR rule.

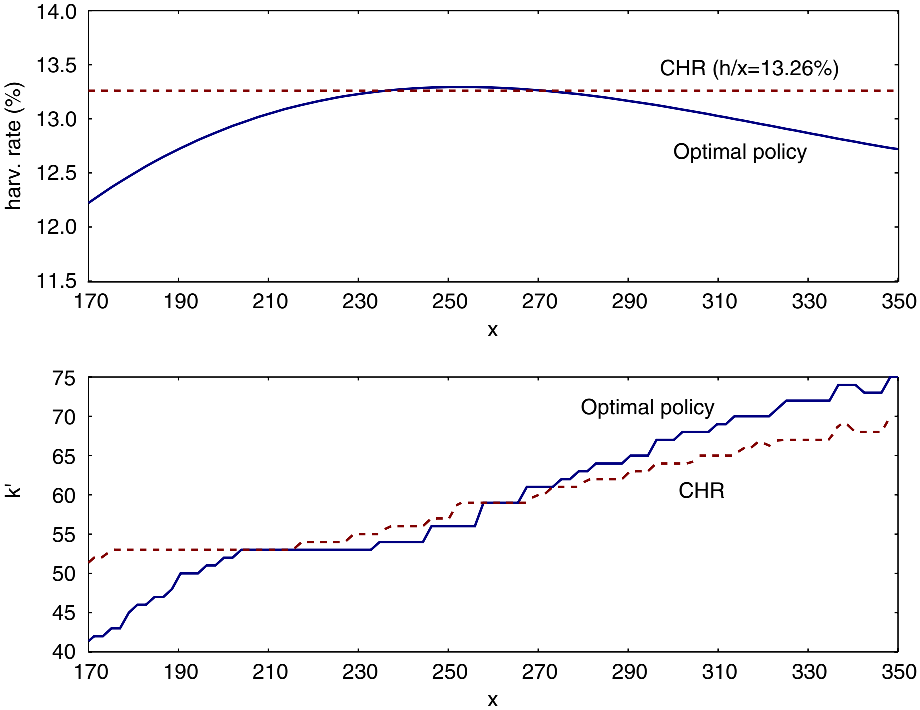

Fig. 3. Harvest and investment under the optimal and CHR policies.

A comparison of the value functions finds that managing the fishery with a value maximizing CHR rule but allowing capital to adjust optimally reduces the value of the fishery by 1–2%. While the CHR rule differs from the optimal policy in its ability to respond to small and large levels of stock abundance, it appears to provide 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. Here we solve for the harvest policy that maximizes the value of the fishery conditional on $k = 583$. We assume a cost of $27,000 is required to refit vessels to fish for halibut each season. This experiment is intended to isolate the effects of the quota trading restrictions currently in place for the Alaskan halibut fleet.

The results in column 3 indicate that mean escapement is smaller and less variable than under the optimal policy. This is explained by the *flattening* of the harvest net benefit function under a 583 vessel fleet. Observe that on average the catch per boat is a mere 53.26 thousand pounds, which is only 10.1% of the catch per boat under the optimal policy. At these low levels for h/k, variation in the catch per boat implies only small changes in marginal harvest costs and consequently, the incentive to smooth the harvest is less important. Turning to the economic welfare measures, we find that mean consumer surplus changes very little. Industry profits under the large and fixed fishing fleet are roughly 35% of 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. This scenario represents the current management program in the Alaskan pacific halibut fishery. We report results for the fishery value maximizing CHR, conditional on $k = 583$. The results indicate that the harvest rate is smaller than the average harvest rate under the optimal policy (column 1) resulting in higher average escapement. Escapement is more variable under the CHR rule, than under the optimal policy.

Comparing the results in columns 2 and 4 shows that, faced with a fleet size fixed at 583 boats, the manager should reduce the CHR from 13.26% to 11.50%, and maintain a larger stock size. The explanation for this result is that the average costs savings from maintaining a large in situ stock are more important when spread across the much larger number of boats.

A comparison of value functions indicates that quota trading restriction, which maintain the harvest fleet at almost 10 times larger than the optimal fleet size, reduce the value of the fishery between 13% and 19%. It should be emphasized that our model is calibrated to Management Unit 3A and assumes the halibut fleet consisting of class 2 boats. Estimates of lost fishery value could also be affected by errors in calibration. The results should be interpreted accordingly.

5. Conclusion

This paper solves for the optimal management policy in a fishery that is subject to stock growth uncertainty and costly capital adjustment. Value function iteration is used to obtain numerical solutions. With costly capital adjustment, marginal net harvest benefits diminish with the catch. This provides an incentive to smooth harvest over time. Harvest smoothing implies increased variability of the in situ fish stock. With density-dependent stock growth, high variability of the stock will imply low-average harvest yield. We show that maximizing the value of a fishery involves an optimal level of catch smoothing in order to balance these trade-offs.

Our results demonstrate the importance of jointly determining harvest and capital investment. Increased fleet size raises the immediate harvest value of the fish stock. All else equal, the fishery manager should increase current period catch if the fishing fleet is large, and leave more fish in the sea if the fleet is small. Leaving more fish for future harvest allows time to invest in more fishing boats which can harvest the surplus stock at lower cost and increase fishery value.

Viewed from the capital investment perspective, the harvest policy determines the level and variability of the stock and harvest over time and consequently determines the value of vessel capital employed in the fishery. The capital investment incentives associated with a particular harvesting rule must be carefully considered if the management goal is to maximize fishery value.

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 by the manager.[19] 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 easily adopted to analyze the effects of the above or other sources of uncertainty on the optimal harvest and investment policies.

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