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Overharvesting the traditional fishery with a captured regulator

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OVERHARVESTING THE TRADITIONAL FISHERY WITH A CAPTURED REGULATOR

by

Peter Berck and Christopher Costello

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Overharvesting the traditional fishery with a captured regulator

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December 4, 2000

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Abstract

Rent dissipation in open access fisheries is a well studied problem (Gordon 1954; Homans and Wilen 1997). Regulation is seen as a possibly remedy to the externality of entry, which eventually leads to zero profits and depressed stocks. Despite regulation, drastic declines have occurred in many regulated fisheries worldwide, prompting a discussion of economic, biological, and environmental phenomena that may lead to declines. We explore one case when a regulator permits overfishing in the context of a traditional fishery model. Influenced by industry to reduce effort restrictions, regulators often rely on gear, season length, and other efficiency restrictions to achieve management goals. Under standard assumptions we find that when the regulator is "captured" by the members of the industry, he unambiguously allows overfishing by reaching a lower stock and higher effort than is socially optimal. This steady state has zero rents, but a higher stock and higher effort than the open access steady state.

Key Words: overfishing, open access, capture.

1 Introduction

Marine fisheries in the United States are regulated by eight regional fishery management councils pursuant to the Magnuson-Stevens Fishery Conservation and Management Act (1976, most recently amended 1996). The act specifies that the fisheries are to be managed for maximum sustainable yield, yet many populations have been reduced to well below this level, often leading to complete fishery closures. The Northeast cod fishery provides a notorious example of collapse. More recently catastrophic declines have been realized for several Pacific salmon stocks, bluefish in the South Atlantic, abalone and numerous groundfish in the Pacific, and many others[1] (Pacific Fishery Management Council 2000).

Others have noted that the councils are made of of members of the industry and very responsive to the needs of the industry, called "capture" in the industrial organization literature (Karpoff 1987). One empirically observed consequence of industry influence is the unwillingness of fishery managers to regulate effort (Thompson Jr. 2000; Johnson and Libecap 1982). This paper explores when, in the context of the traditional Schaeffer model, a captured regulator will permit overfishing.

The layout of the paper is as follows. In the next section, we provide some background information on the Magnuson Act and the Sustainable Fisheries Act, which naturally lead into a discussion of the way many U.S. fisheries are currently managed. In section 2 we introduce the model, where the fishery

[1] All eight management council websites contain current information of stocks, fishery management plans, and regulations. Links can be found in the Pacific Fishery Management Council Site, http://www.pcouncil.org

regulator chooses fishing efficiency to maximize discounted returns while allowing unregulated entry and exit driven by profits. The result is derived in section 2.1, and section 3 describes the steady state. The saddle point properties of the steady state are demonstrated in section 3.1, and are followed by a discussion of the non-equilibrium dynamics in section 3.2. Finally, in section 4 we compare the solution to the familiar extremes of open access and the sole owner, and find that the captured regulator allows overfishing by ignoring a critical component of costs. In so doing, the captured regulator reaches a steady state with completely dissipated rents, a lower stock, and higher effort than chosen by the sole owner. The paper is concluded with a brief illustrative example (section 5), and a discussion in section 6.

1.1 Background and Layout

The Magnuson-Stevens Fishery Conservation and Management Act (FCMA) was originally passed in 1976, and was most recently amended by the 1996 Sustainable Fisheries Act (SFA). Perhaps the most striking accomplishment of the FCMA was to establish exclusive economic zones which, for the U.S., established property rights within 200 miles of the coast. Partly a response to declining fish stocks (from overfishing, inadequate conservation practices, and habitat loss, as stated in the FCMA), this represented an acknowledgement of the role for management of marine fisheries.

Nearly half a century ago the deleterious consequences of open access fisheries were identified (Gordon 1954). More recently Dupont (1990) and others have focused attention towards causes of rent dissipation in restricted access fisheries. Wilen (2000) surveys and evaluates the contribution of fisheries

economists to management and policy since the seminal work of Gordon. He finds that relevant efficiency-generating contributions have been made but that property rights are still not sufficiently strict in many fisheries worldwide to reverse the effects of open access.

Of more direct relevance to this paper, some have focused specifically on the inability of fishery regulators to efficiently offset the rent-dissipating consequences of open access. Johnson and Libecap (1982) argue that government regulators are unlikely to effectively control individual effort, and conclude that fishers are likely to support regulations affecting fishing efficiency (season closures, gear restrictions, and minimum size limitations) and are unlikely to support limited entry, taxes, and fishing quotas.

Karpoff (1987) considers the regulated fishery problem as a matter of choosing season length and the capital per boat (catchability coefficient). His static analysis shows that these two commonly employed policy instruments have different distributional effects. In his view, the fishery regulator is captured and uses the policy instruments to favor one group of fishers over another. Free entry, with each vessel's catch decreasing, is seen as a political outcome, while additional fishers are viewed as stimulating more political support.

Homans and Wilen (1997) focus exclusively on season length restrictions and allow endogenous entry. Their model is motivated by the observation that most fisheries are not purely open access, and are heavily influenced by regulation. In an application to the North Pacific halibut fishery, they predict a shorter fishing season, but a higher biomass, harvest, and capacity under regulation than under pure open access.

Our paper adopts the assumption of a regulator captured by members of the industry (as in Karpoff). We model the captured regulator as a fishery manager who is unable to restrict entry, and therefore chooses the politically viable option of controlling parameters of fishing technology, or catchability (see Johnson and Libecap). Like Homans and Wilen, the model in this paper facilitates making bioeconomic predictions across multiple regulatory paradigms. We take open access as given (indeed Congress imposed a moratorium on new IFQ programs until October, 2000). In a dynamic framework, we explore the regulator's optimal choice of fishing efficiency to maximize the discounted payoff to a representative fisher.

1.2 Fishery Management in the U.S.

In the U.S., most commercial fisheries are strictly managed. In addition to creating economic zones, the Magnuson Act mandated the establishment of eight regional management councils[2] each charged with task of creating fishery management plans for economically important fisheries within their jurisdiction. Fishery management plans provide parameters which help guide management such as optimum yield and harvest guidelines (see Pacific Fishery Management Council (2000) for excellent examples). Development of a fishery management plan by one of the regional councils grants authority to the U.S Secretary of Commerce to regulate as described in the plan. To take effect, the plan must be adopted by the Secretary of Commerce.

Fishery management plans and proposed amendments must be presented

[2]Regional fishery management councils are Caribbean, Gulf, mid-Atlantic, New England, North Pacific, Pacific, South Atlantic, and Western Pacific.

to the public (including industry representatives) for review and comment prior to their adoption. Language in the Magnuson Act requires consideration of economic and social components of fishery management. Various interests are included by design, and the typical management council composition includes members representing commercial fishers, processors, and recreational anglers. Institutional pressure imposed by fishing interests on regulators have lead some to suggest that regional councils are captured by fishing interests (Shelley, Atkinson, Dorsey, and Brooks 1996; Karpoff 1987). In some cases management actions are heavily influenced by industry interests. For example, fishermen's opposition to trip limits in the New England cod, haddock, and yellowtail flounder fisheries was, in part, responsible for the inability to enforce effort restrictions. In the early 1980's, effort controls were eventually removed, and subsequently lead to significant increases in fishing pressure on these stocks (Thompson Jr. 2000).

Section 107 of the Sustainable Fisheries Act largely focuses on potential management council member's conflicts of interest; suggesting the importance of studying the influence of fishing interests in council policies. In reference to the conflict of interest provisions in the SFA, President Clinton voices concern that it "does not provide adequate protection against conflicts of interest on the part of members of the fishery management councils" (President of the United States 1996). This paper does not directly address the mechanism allowing industry capture of the regulator, but takes capture as a given. In this case, a captured regulator is influenced to act in the best interest of industry participants (by maximizing net present value to them), but allows free entry. One popular mechanism fishery regulators use

to regulate entry is the individual fishing quota (IFQ). However, the Sustainable Fisheries Act established a four year moratorium on new IFQ programs which ended in October, 2000.

Without the ability to regulate entry, the regulator achieves the legal requirements of the Magnuson Act and its amendments through manipulation of parameters of the fishing technology, a common management practice in the U.S. and abroad. Clearly this will lead to a second-best outcome, with a lower payoff than could be achieved through effort restrictions. However the effect on dynamics and steady state of effort and fish stock are not obvious. This paper demonstrates that while the captured regulator's fishery has higher stock and higher effort than the open access equilibrium, there are zero rents, lower stock, and higher effort than the sole owner would optimally choose.

2 Model

The model begins with the Schaeffer model of a fishery in continuous time. Stock, $X(t)$, grows at rate $f(X)$ (which we do not have to assume is quadratic), and is harvested at rate, $h(t)$. All of these variables are functions of time, though for notational simplicity we omit t. There are E boats and each boat catches kX fish per unit time, so $h = kEX$, where k measures the proportion of the stock harvested by each boat[3]. Results of this analysis are likely to

[3]The traditional bilinear form of harvest being proportional to the product of effort and stock can be generalized, though in the interest of minimizing algebraic clutter, we adhere to tradition. The simplest (and most benign) generalization is to allow $h = kE\phi(X)$ for some function $\phi(\cdot)$, though a complete generalization of $h = h(k, E, X)$ would significantly increase mathematical complexity (mostly because the objective would no longer be linear

continue to hold for more general functional forms for the harvest function, though the analytics become significantly more involved. For illustrative purposes, we adhere to the traditional bilinear form above where harvest is proportional to the product of effort and stock. The growth of the stock is therefore

$$\dot{X} = f(X) - kEX. \tag{1}$$

As in the open access model, boats enter in proportion to current individual profits (see Berck and Perloff (1984) for the much more complicated case where entry is proportional to present value of profits). Price of fish p and costs per unit time per boat c are both constant. The constant of proportionality is δ. The units of δ are boats per dollar, representing the number of boats that enter the fishery per dollar of profit instantaneously observed in the fishery. Thus the rate of change of the effort in this fishery is:

$$\dot{E} = \delta(pkX - c). \tag{2}$$

Implicit in this formulation is the assumption that boats currently participating in the fishery spend the same amount of time fishing, and therefore are homogeneous with respect to revenue and costs. Symmetric entry and exit rates are adopted for modeling convenience. The regulator acts in the interest of the representative fisher currently in the industry, and credibly continues to behave this way throughout time. The decision of whether to enter the industry, however, is made solely on the basis of current profits, i.e. potential entrants are myopic about profits.

in k), and would reduce tractability of results.

In order to meet the goals of regulation, the fishery management agency can close part or all of the fishery for part or all of the season. It can also regulate the gear used, including the mesh size of the net, use of monofilament nets, spacing of hooks, horsepower of vessels, and so on. The policy instrument is the efficiency of fishing, k, allowing entry and exit to occur unregulated. Traditional models of fishery management take the "catchability coefficient" k as exogenously given. Without regulation, we assume fishers operate at the maximum efficiency allowed by their equipment, $\bar{k}$. Here, we abstract from the exact form of regulation and model the regulation as the agency choosing $k(t) \in [\underline{k}, \bar{k}]$. The captured agency maximizes the present value of future profits to the representative fisher discounted at rate, r, as follows:

$$\max_{k(t)\in[\underline{k},\bar{k}]} \int_0^\infty e^{-rt}(pkX - c)dt \tag{3}$$

subject to (1) and (2). Here k, E, and X may all vary through time.

The current value Hamiltonian for this problem is:

$$H(X, E, k, \lambda, \gamma) = (1 + \delta\gamma)(pkX - c) + \lambda(f(X) - kEX). \tag{4}$$

The associated costate equations defining the shadow value of fish stock (λ) and the shadow value of effort (γ) as functions of time are:

$$\dot{\gamma} - r\gamma = \lambda kX \tag{5}$$

$$\dot{\lambda} - r\lambda = -\lambda(f' - kE) - (1 + \delta\gamma)pk. \tag{6}$$

The captured regulator seeks to choose the time path of k which maximizes

the Hamiltonian. Since H is linear in k, a bang-bang solution is optimal, where $\bar{k}$ or $\underline{k}$ is chosen until the convergent path is reached, at which time k is set to be interior so that $H_k = 0$. Next, we describe the convergent path, and associated interior choice of k.

2.1 The Exceptional Control

The exceptional control (where k is interior) is found by first finding where the derivative of H with respect to k vanishes,

$$H_k = pX(1 + \delta\gamma) - \lambda EX = 0. \tag{7}$$

Since H is linear in k, this expression defines a curve in X, E space. We solve (7) for γ as follows:

$$\gamma = \frac{\lambda E}{\delta p} - \frac{1}{\delta} \tag{8}$$

and substitute into the costate equation for γ to get

$$\dot{\gamma} - r\gamma = \frac{\dot{\lambda}E + \lambda\dot{E}}{\delta p} - \frac{rE\lambda}{\delta p} + \frac{r}{\delta} = \lambda k X. \tag{9}$$

Now we use the costate equation for λ and the state equation for E to solve for

$$-\frac{\lambda f' E}{p\delta} - \frac{\lambda c}{p} + \frac{r}{\delta} = 0 \tag{10}$$

and differentiate and solve to get

$$-\frac{\dot{\lambda}}{\lambda} = \frac{f''\dot{X}E + f'\dot{E}}{f'E + c\delta}. \tag{11}$$

We substitute $p(1+\gamma\delta) = \lambda E$ (from $H_k = 0$) into the state equation for λ to get

$$-\frac{\dot{\lambda}}{\lambda} = f' - r. \tag{12}$$

So, for an exceptional control,

$$\frac{f''\dot{X}E + f'\dot{E}}{f'E + c\delta} = f' - r. \tag{13}$$

Substitutions for $\dot{X}$ and $\dot{E}$ and solving this expression for k^* gives the explicit closed-form solution

$$k^* = \frac{f'E(f'-r) + 2f'\delta c - r\delta c - ff''E}{f'\delta pX - f''E^2X}. \tag{14}$$

This equation gives the explicit solution for the exceptional control, k^* as a function of effort E and stock X at any time. A sufficient condition for $k^* > 0$ is $f' \geq r$. The curve in x, E space traced by the points where X, E, and $k^*(X, E)$ are such that $H_k = 0$ is the convergent path about the equilibrium for this system.

3 Steady State and Dynamics

There are two possible ways for this system to have a steady state as part of an optimal program: either k is the exceptional control or it is an extreme control. Let us begin with the possibility of a steady state with an exceptional control.

Setting the time derivative of λ equal to zero and substituting as before from $H_k = 0$ yields $f'(X_{ss}) = r$. Since $\dot{E}$ must be zero in a steady state,

$k_{ss} = \frac{c}{pX_{ss}}$. From $\dot{X} = 0$, $E_{ss} = \frac{f(X_{ss})p}{c}$. $H_k = 0$ and $\dot{\gamma} = 0$ are two equations for λ and γ with solution

$$\lambda = \frac{prc}{c^2\delta + f(X_{ss})pr} \tag{15}$$

$$\gamma = \frac{-rc^2}{c^2\delta + f(X_{ss})pr}. \tag{16}$$

Note that $\lim_{t\to\infty} e^{-rt}\gamma = \lim_{t\to\infty} e^{-rt}\lambda = 0$. This demonstrates that there is a steady state solution for X, k, and E that satisfies the necessary conditions and also satisfies the transversality condition (Michel 1982). For this to be a steady state it must be that $\underline{k} < k_{ss} < \bar{k}$ and it is assumed that this is the case.

Most fishery growth models assume $f(0) = 0$. In this model, this implies that there is an $\dot{X} = 0$ nullcline at $X = 0$. This may give rise to an alternative steady state at $X = 0$, $E = 0$ (since, when $X = 0$, $\dot{E} = -\delta c < 0$). Thus, if the prescribed $k^*(X, E)$ policy is followed, we will either end up at a stock level of 0 or a stock level where $f'(X_{ss}) = r$. The optimal stock level is the interior solution, but the feasibility of attaining that level is determined by parameters of the model, as shown in the next section.

3.1 Near Equilibrium Dynamics

Phase plane analysis can be used to describe the dynamics of this system in the vicinity of the steady state identified above. We will produce a two dimensional plot of the state variables, E and X, with the optimal control, k^* implicitly defined. To facilitate this analysis, we make use of equation (13), the equation which implicitly describes the optimal fishing efficiency,

k^*. Rewritten, this equation is as follows:

$$f''\dot{X}E + f'\dot{E} = (f' - r)(f'E + c\delta).$$

Using this "fundamental equation", we find $\frac{dk^*}{dE} \equiv k_E^*$ and $\frac{dk^*}{dX} \equiv k_X^*$ near the steady state. We obtain the following result:

$$k_E^* = \frac{f''EXk}{f'\delta pX - f''E^2X} \quad < 0 \tag{17}$$

$$k_X^* = \frac{f''(c\delta + E^2k) - f'\delta pk}{X(f'\delta p - E^2f'')} \quad < 0. \tag{18}$$

These equations hold at the steady state, where $\dot{X} = \dot{E} = \dot{k} = 0$.

The slopes of the $\dot{E} = 0$ and $\dot{X} = 0$ nullclines near the steady state are given as follows:

$$\left.\frac{dE}{dX}\right|_{\dot{X}=0} = \frac{f' - E(k_X X + k)}{X(k_E E + k)} \tag{19}$$

$$\left.\frac{dE}{dX}\right|_{\dot{E}=0} = \frac{-(k_X X + k)}{Xk_E}. \tag{20}$$

To sign these slopes, we need to determine the sign of $k_X X + k$ and $X(k_E E + k)$. We obtain the following:

$$k_X X + k = \frac{f''(c\delta + E^2k) - f'\delta pk + k(f'\delta p - E^2f'')}{f'\delta p - E^2f''} = \frac{f''c\delta}{f'\delta p - E^2f''} \quad < 0 \tag{21}$$

$$X(k_E E + k) = \frac{k(XE^2f'' + Xf'\delta p - XE^2f'')}{f'\delta p - E^2f''} \quad > 0. \tag{22}$$

This unambiguously gives the signs of the slopes of the nullclines near the

steady state as follows:

$$\left.\frac{dE}{dX}\right|_{\dot{X}=0} > 0 \tag{23}$$

$$\left.\frac{dE}{dX}\right|_{\dot{E}=0} < 0 \tag{24}$$

Thus, near the steady state the $\dot{X} = 0$ nullcline slopes up while the $\dot{E} = 0$ nullcline slopes down.

In the vicinity of the steady state this system has four isosectors (see Figure 1). Let $I1$ be the isosector below $\dot{E} = 0$ and above $\dot{X} = 0$, and let $I2$, $I3$, and $I4$ be the remaining isosectors (clockwise from $I1$, respectively). Then isosectors $I1$ and $I3$ are terminal isosectors since once the stock/effort system is in one of these sectors, it cannot escape (without further manipulation of k).

Stability of the steady state is determined by computing the eigenvalues of the Jacobian (matrix of first partial derivatives) evaluated at the steady state. The Jacobian, A, is given by

$$A = \begin{bmatrix} \frac{\partial \dot{X}}{\partial X} & \frac{\partial \dot{X}}{\partial E} \\ \frac{\partial \dot{E}}{\partial X} & \frac{\partial \dot{E}}{\partial E} \end{bmatrix} = \begin{bmatrix} f' - E(k_X X + k) & -X(k_E E + k) \\ \delta p(k_X X + k) & \delta p X k_E \end{bmatrix} = \begin{bmatrix} + & - \\ - & - \end{bmatrix}. \tag{25}$$

The determinant of A is negative ($|A| < 0$), so there is one positive, and one negative eigenvalue of this system. The steady state is therefore a saddle point with a convergent path of dimension one in $\{X, E\}$ space. The slope of this convergent path is given by the eigenvector associated with the negative eigenvalue. Directional arrows reveal that the slope of the convergent path is positive. A picture of this system near the steady state is given in Figure

1. In the figure, the convergent lies in sectors $I2$ and $I4$.

3.2 Non-Equilibrium Dynamics

Figure 1 demonstrates the optimal dynamics toward the steady state along the convergent path. But, what if the system starts out off of the one-dimensional convergent path (given by the dotted line in Figure 1)? In that case, k should be set to intersect the convergent path as rapidly as possible. From equation (7) the slope of the Hamiltonian with respect to E is negative. Thus, if we move up (left) of the convergent path, we maximize the Hamiltonian by choosing the smallest possible control, $\underline{k}$. On the other hand, since the Hamiltonian is increasing in k below (right) of the convergent path, we should choose the largest possible control, $\bar{k}$ to hit the convergent path as quickly as possible.

When the regulator chooses an extreme control ($\underline{k}$ or $\bar{k}$), the dynamics are identical to those of the open access fishery. The dynamics are given by the differential equations

$$\dot{X} = f(X) - \tilde{k}EX \tag{26}$$

$$\dot{E} = \delta(p\tilde{k}X - c) \tag{27}$$

where $\tilde{k}$ is a fixed catchability (either $\underline{k}$ or $\bar{k}$ in the captured regulator's case). The steady state of this system is $X = \frac{c}{p\tilde{k}}$ and $E = \frac{f(X)}{\tilde{k}X}$ and the Jacobian, B, is given by

$$B = \begin{bmatrix} f' - \tilde{k}E & -\tilde{k}X \\ \delta p\tilde{k} & 0 \end{bmatrix}. \tag{28}$$

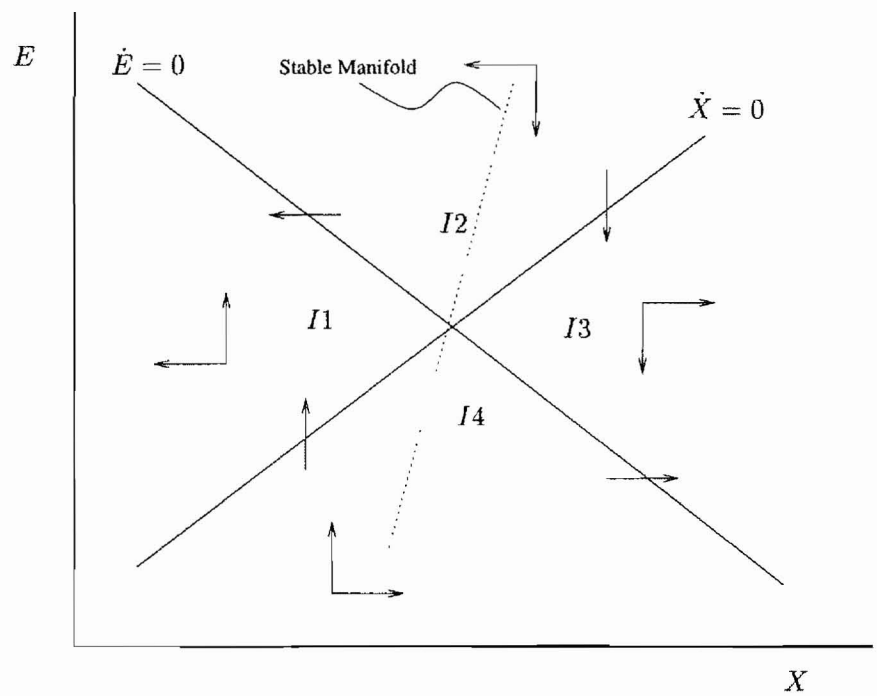

Figure 1: Nullclines for the captured fishery model in $\{X, E\}$ space with implicit optimal fishing efficiency, $k^*(X, E)$. This is a saddle point equilibrium where the convergent path is of dimension one with positive slope, represented by the dotted line.

The Jacobian B has a positive determinant. The trace of B is negative provided $\frac{f(X)}{X} > f'(X)$, guaranteeing an asymptotically stable steady state[4]. Comparative statics on the steady state reveal $\frac{dX}{dk} < 0$. That is, in an open access fishery, an increase in fishing efficiency tends to decrease the equilibrium fish stock.

The optimal policy for the captured fishery is qualitatively summarized as follows: When effort is high and the stock is low (i.e. to the right of the dotted line in figure 1), the regulator should set $k = \bar{k}$. Alternatively, when effort is low and the stock is high (to the left of the dotted line), the regulator should set $k = \underline{k}$. These actions move the system towards the dotted line (through entry/exit and changes in stock size) as quickly as possible. Once the convergent path is reached, an intermediate level of efficiency is set, eventually driving the system to steady state. We now turn to a comparison between the captured regulator (who controls fishing efficiency)and the sole owner (who controls effort).

4 Captured Regulator Versus the Optimum

How does the captured regulator's fishery compare to the optimum? Overfishing is judged relative to the optimal case of the sole owner who chooses effort while enjoying the largest possible catchability, $\bar{k}$[5]. The sole owner

[4]The condition requires the average growth rate to exceed the marginal growth rate. For example, the condition holds for the logistic growth function.

[5]Positive effort cost, $c > 0$, makes it more cost effective for the sole owner to achieve a given harvest with high k and low E rather than achieving the same harvest with low k and high E. If costs are negligible, either effort or fishing efficiency could be controlled.

solves

$$\max_{E(t)\in[\underline{E},\bar{E}]} \int_0^\infty e^{-rt} E(p\bar{k}X - c) \tag{29}$$

$$s.t. \quad \dot{X} = f(X) - \bar{k}EX. \tag{30}$$

The steady state stock for the sole owner is given implicitly by

$$f'(X_{ss}^S) = r - \bar{k}E_{ss}^S\left(\frac{c}{p\bar{k}X_{ss}^S - c}\right) < r \tag{31}$$

where superscript S refers to the sole owner. Unlike the captured regulator who chooses catchability (k) to maximize his Hamiltonian (which is linear in k), the sole owner faces a Hamiltonian linear in her control, E, and must therefore choose $\bar{E}$, the highest level of effort possible, if $X < X_{ss}^S$ and choose $\underline{E}$ if $X > X_{ss}^S$. When the stock gets to the point where $X = X_{ss}^S$, the regulator immediately adjusts $E = E_{ss}^S$, and maintains the steady state at that level.

In steady state the sole owner chooses an effort level to satisfy the equality in (31). Unlike the captured regulator, the sole owner accounts for the stock effect on costs. As this effect increases (higher c), the optimal stock level for the sole owner increases. Not so for the captured regulator, however. The inequality in (31) holds because $p\bar{k}X > c$. By the concavity of $f(X)$ we observe that the steady state value of stock for the captured regulator is unambiguously smaller than that of the sole owner. The captured regulator allows overfishing by ignoring the stock effect on costs. Without a stock effect on costs (if $c = 0$) the two steady states are identical.

What about the steady state level of effort under the two scenarios? A sufficient condition for the steady state level of effort for the captured

regulator to be larger than that of the sole owner is the following:

$$\frac{d\frac{f(x)}{x}}{dx} < 0. \tag{32}$$

That is, the stock grows at a slower percentage rate for higher stocks than for lower stocks. This condition is satisfied by many growth functions, including the logistic. Since $X_{ss}^S > X_{ss}^C$, by (32) we have, $\frac{f(X_{ss}^S)}{X_{ss}^S} < \frac{f(X_{ss}^C)}{X_{ss}^C}$. We also know $\bar{k} > k_{ss}^*$. Thus, $E_{ss}^S < E_{ss}^C$. In the steady state, the captured regulator allows greater effort, reduces the stock to a lower level, and impose lower harvest efficiency than the sole owner. These relationships between steady state values of X, E, and k under open access, the captured regulator, and the sole owner are shown in the following table:

Variable	Open Access	Captured Fishery	Sole Owner
X	$\frac{c}{p\bar{k}}$	$f'(X) = r$ or $x = \frac{c}{pk^*}$	$f'(X) = r - \frac{cf(X)}{X(p\bar{k}-c)}$
E	$\frac{f(X)p}{c}$ or $\frac{f(X)}{kX}$	$\frac{f(X)p}{c}$	$\frac{f(X)}{kX}$
k	$\bar{k}$	$\underline{k} < k^* < \bar{k}$	$\bar{k}$

And $X^{OA} < X^C < X^S$, and $E^S < E^{OA} < E^C$ where superscripts stand for open access (OA), captured (C), and sole owner (S).

5 Example

To briefly illustrate the dynamics of this model, we develop an example based on the familiar logistic growth model of a fishery. The growth rate in the absence of harvest is

$$f(X) = gX(1 - \frac{X}{K}) \tag{33}$$

where g is the intrinsic growth rate and K is the carrying capacity of the stock. The parameter choices are made for illustrative purposes and are not intended to represent any particular fishery. Parameter values used in this example are given in the table below.

Parameter	Description	Value
r	discount rate	0.05
p	price	30
c	cost parameter	5
δ	entry rate (per profit)	.5
K	carrying capacity	100
g	intrinsic growth rate	.2
$\bar{k}$	maximum fishing efficiency	.007
$\underline{k}$	minimum fishing efficiency	.0033
$\bar{E}$	maximum effort for sole owner	55
$\underline{E}$	minimum effort for sole owner	5

Figure 2 depicts the dynamics of all three models given the above parameter values, and two different starting points. The "good" starting state is indicated by a circle, with high stock and low effort. The "bad" starting state is indicated by a square and has low stock and high effort. The remainder of this section compares the dynamics of each of model starting from each of the two starting states.

As explained above, the sole owner has an objective which is linear in her control, effort. If she finds herself in the $\left\{\begin{smallmatrix} good \\ bad \end{smallmatrix}\right\}$ state, she maximizes rents by setting $\left\{\begin{smallmatrix} \bar{E} \\ \underline{E} \end{smallmatrix}\right\}$, represented by the dotted lines in Figure 2. Following this

strategy, the sole owner eventually reaches a stock/effort level given by the diamond in the figure, with high stock and low effort.

The consequences of open access are easily seen by comparing the solely owned fishery with the fishery owned by nobody (or everybody). With open access, dynamics and the eventual steady state depend upon the fishing efficiency parameter, k, which is fixed. When $k = \underline{k}$ and the starting state is bad, effort drops leading to an increase in the stock size, dynamics graphed by the dashed path. One the other hand, if the starting state is good, and if $k = \bar{k}$, the dash-dot path is followed. For the parameter values chosen here, both open access steady states (depending on which value of k was assumed) have higher effort, and lower stock than the sole owner steady state. In fact, this relationship holds true regardless of parameter values.

The final case to be graphically explored by Figure 2, is that of the captured regulator. Recall that the optimal policy of the captured regulator is to set k equal to $\underline{k}$ or $\bar{k}$ for some time, and then to adjust k to reach the steady state along the convergent path[6]. In the figure, if the captured regulator starts in the good state, he optimally follows the dash-dot line by setting $k = \bar{k}$, following the dash-dot path, reducing the stock size, and increasing the effort level until the convergent path (solid line) is hit. Efficiency k is then chosen at an interior level until the steady state ($*$) is reached. Similarly, starting in the bad state, k is set to its lowest value, allowing stock to

[6]The convergent path is found by numerically calculating the eigenvector associated with the negative eigenvalue of the Jacobian evaluated at the steady state. Differential equations for $\dot{X}$ and $\dot{E}$ along with the definition $k^*(X, E)$ are used to trace out the convergent path from a small perturbation away from the steady state, along the obtained eigenvector. Dynamics for the sole owner and open access fisheries are superimposed on the same graph. All figures and numerical calculations are done in MATLAB.

rebound, and causing exit in the industry, until the convergent path is hit. Efficiency is then adjusted to reach the steady state.

One interesting observation about the captured regulator's management in this example is that the effort is non-monotonic. That is, starting from the "bad" state, the initially high effort is driven down below the steady state level, and is eventually encouraged back up by slackening restrictions on k. Starting from the "good" state, k is set so low that fishers enter the industry, driving down stock. But they enter so fast that some are eventually driven out by decreases in k along the convergent path .

6 Discussion

Recent declines in many managed fisheries worldwide raises questions about the efficacy of management regimes. If fishery management agencies are heavily influenced by fishers, the agency is said to be "captured" by the members of the industry. We model a captured regulator as one who is influenced to allow free entry, but who chooses efficiency-related controls such as area closures, gear restrictions, and season lengths to achieve management objectives. The regulator acts in the best interest of the representative fisher in the industry. In the context of a common, simple fishery management model, we explore when a captured fishery regulator will allow overharvesting. We show that despite the regulator's goal of maximizing the net present value of harvest, he unambiguously allows overfishing. Essentially the regulator ignores stock effects on harvest costs, causing higher effort and lower stock than are suggested by optimal management.

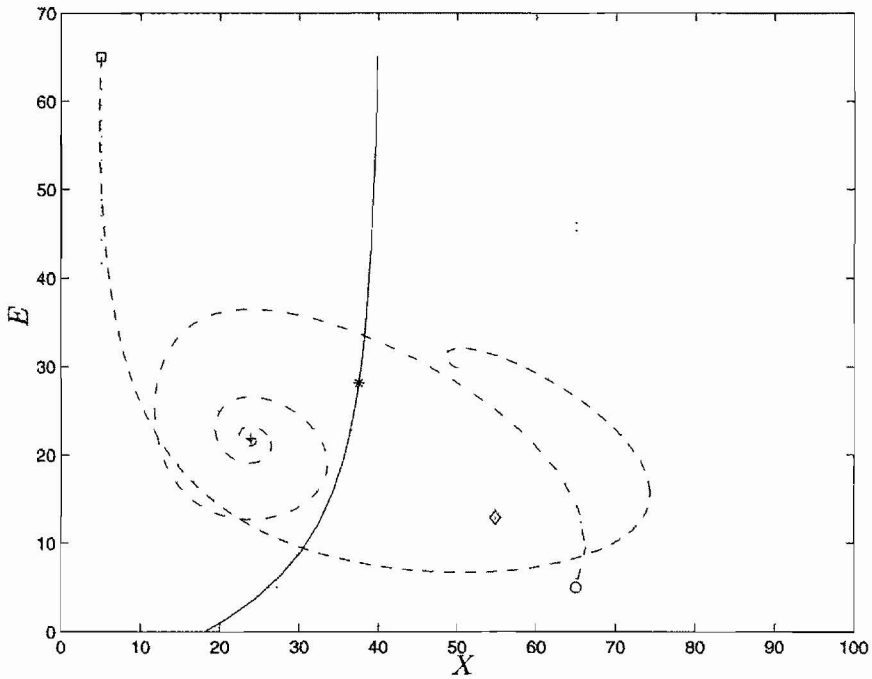

Figure 2: Dynamics of all three models, starting from "good" (circle) and "bad" (square) states. (1) Starting from either state, the sole owner chooses either $E = \bar{E}$ or $E = \underline{E}$, following the dotted graph to the sole owner steady state given by the diamond. (2) In the open access model, an oscillatory route is followed to steady state. Starting from the "good" state and if $k = \bar{k}$, the open access model moves according to the dash-dot graph. Starting from the "bad" state and if $k = \underline{k}$, the open access model moves according to the dash graph. (3) Starting from the "good" state, the captured regulator follows the path of the open access model with $k = \bar{k}$ until the convergent path (solid line) is reached. Starting from the "bad" state, the captured regulator follows the open access path with $k = \underline{k}$ until the convergent path is reached. Once the convergent path is reached, the captured regulator sets intermediate levels of fishing efficiency, k, and moves along the convergent path to the steady state (given by the $*$).

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