Efficiency Controls and the Captured Fishery Regulator

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Advising at Jupiter, a Berkeley watering hole. Christopher Costello and Peter Berck.

Peter passed away on August 10, 2018. This work was drafted before his passing, and Peter looked forward to the day it was published.

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1 Introduction

We consider management of fisheries whose regulators are "captured" by industry in the sense that they cannot directly limit entry and they act in the best interest of their constituents. Although industry capture is often put forth as a cause of fishery declines, few studies have examined the incentives for a captured regulator to deplete the fish stock it controls. At the outset, it is not obvious to what extent regulators (the fishers themselves) will allow overfishing, since they are attempting to maximize discounted profits from future harvest. Whatever the outcome, the two major assumptions of this research—that fishers exert influence over management and that directly regulating entry is a policy tool unavailable to the manager—can be defended on legal, political, and intuitive grounds.

Fisheries are managed in myriad ways around the world[1] but can be loosely classified into three categories. While it is difficult to pinpoint management of all fisheries, around one-third of the world's fish catch is not managed at all and is thus subject to pure open access incentives. These fisheries are primarily located in the developing tropics and are often comprised of coastal, artisanal fisheries. Another third of fish catch comes from well-managed, tightly controlled fisheries whose quotas are set, monitored, and enforced in a more-or-less economically rational manner. These are primarily comprised of the high-value fisheries in North America and Europe, with a few notably well-managed fisheries in South America, Africa, and Asia. The final third, and the one we focus primarily on in this chapter, is comprised of fisheries with some management, but where political pressure leaves an indelible mark on fishery outcomes. Here, instead of setting strict catch quotas, regulators typically identify rough catch targets for the season and impose other restrictions such as gear type, season length, and area closures to loosely meet that target. In these settings, entry is difficult or impossible to control, and management decisions are often made, implicitly or explicitly, under pressure from industry; we follow others who refer to this as "capture" (Karpoff, 1987).

In a recent theoretical and empirical contribution on regulatory capture, (Costello & Grainger, 2018) studied the role of property rights in determining the consequences of fishery capture. In their model, stronger property rights implied that an incumbent fisherman had a higher chance of reaping the benefits of any current conservation action (such as lowering quotas), in a manner similar to Bohn and Deacon (2000). In that setting, the authors showed that a captured regulator sets excessive quotas only when property rights are weak. In other words, stronger property rights lead the regulator to set closer-to-profit-maximizing quotas. While that paper was instructive and helped lay the groundwork for this work,

[1] See Melnychuk et al. (2021), Hilborn et al. (2020), and Costello and Ovando (2019) for overviews and analysis of global fisheries management and effectiveness.

it focused entirely on quota-managed fisheries with existing stock assessments. Instead, we wonder how industry capture affects fisheries that are poorly or only loosely managed, often by input controls such as gear and season restrictions. One empirically observed consequence of industry influence in these latter settings is the unwillingness of fishery managers to regulate entry (Thompson, 2000; Johnson & Libecap, 1982); this will become central to our story and distinguishes this contribution from its predecessors.

Thus, we take it as given that neither harvest nor entry can be directly controlled, leaving technology as the only instrument available to the regulator. The captured regulator is faced with a dilemma where entrants look just like incumbents, and therefore profits must be maximized for the representative fisher participating in the fishery at any point in time. At first glance, it appears that such a regulator would want to set fishing efficiency as high as possible because that maximizes the short-run profits to incumbent fishers. But if fishing efficiency is too high, current profits will spur entry, and profits to those currently in power will fall. On the other hand, if fishing efficiency is too low, current profits will be negative. This chapter addresses this tradeoff and solves for the optimal management of such a captured fishery regulator. We find that, in fact, the captured regulator allows excessive harvest, resulting in an equilibrium with completely dissipated rents and inefficiently excessive effort. We compare dynamics and equilibria with those of the sole owner and open access.

The layout of the chapter is as follows. In the next section, we provide some background information on current management of fisheries in the USA and elsewhere in the world. In Sect. 2, we introduce the model, where the fishery regulator chooses fishing efficiency to maximize discounted returns while allowing unregulated entry and exit driven by profits. The aforementioned results are derived in Sects. 2.1, and 3 describes the steady state. The saddle point properties of the steady state are demonstrated in Sect. 3.1 and are followed by a discussion of the non-equilibrium dynamics in Sect. 3.2. Finally, in Sect. 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 chapter concludes with a brief illustrative example (Sect. 5) and a discussion in Sect. 6.

1.1 Background

There exists a rich and growing literature dealing with management of fisheries. One seminal paper upon which this literature is built is Vernon Smith's 1968 AER paper, which treats effort[2]—defined by Smith as the number of fishing boats or

[2] Smith uses K to denote effort. In an unfortunate choice of notation, the subsequent literature uses E for effort and k for a measure of "catchability." We adopt the latter notation in this model.

firms—as the choice variable by the regulator or firms. Clark et al. (1979) contribute to this literature by analyzing the exploitation of a fishery where the maximum effort capacity is finite. The irreversibility of capital investment they build into the model does not impact equilibrium results but has important implications for short-run dynamics, much like the results we obtain. Like Smith's interpretation and the one adopted here, Clark et al. interpret the amount of capital invested in the fishery at any given time as the number of standardized fishing vessels. Our model departs from the models of Smith, Clark et al., and most of the other fishery literature in one critical sense. In our model, the regulator cannot limit entry into the fishery and is therefore forced to control harvest by regulating fishing efficiency. This is an admittedly sub-optimal instrument.

The conceptual and theoretically derived deleterious consequences of open access fisheries are widely appreciated (Gordon, 1954). These results have recently been substantiated empirically by Kelleher et al. (2009) and Costello et al. (2016), who estimate the efficiency loss, and conservation implications, of mis-managed fisheries around the world. While fisheries in the United States are now among the world's best-managed (Hilborn et al., 2020), this was not always the case. Until about 2010, there was a commonly held view among industry participants that fishery managers in many US fisheries were reluctant to directly regulate harvest or effort. Indeed, a large fraction of global fisheries fit into this category, where well-intentioned fishery managers cannot directly regulate entry or catch, but can and do exert regulatory influence by restricting the technology of fishing. Exploring the middle ground of this regulatory landscape are early papers by Dupont (1990), Homans and Wilen (1997), and others who study "restricted access" or "regulated open access" fisheries, where, for example, the regulator chooses an instrument such as season length to manage the fishery. 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.

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.[3]

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.

[3] However, many fishers may support limited entry if they are guaranteed inclusion.

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 higher biomass, harvest, and capacity under regulation than under pure open access.

Our work adopts the assumption that the regulator is captured by members of the industry (as in Karpoff (1987) and Costello and Grainger (2018)). We model the captured regulator as a fishery manager who is unable to restrict entry and therefore controls fishing technology or catchability (see Johnson and Libecap 1982).[4] Like Homans and Wilen, the model in this chapter facilitates making bioeconomic predictions across multiple regulatory paradigms. We take as given the inability to directly regulate harvest or entry. In a dynamic framework, we explore the regulator's optimal choice of fishing efficiency to maximize the discounted payoff to a representative fisher.

Without the ability to control entry, the regulator achieves management goals through manipulation of parameters of the fishing technology, a common management practice in the USA 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 chapter 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 Schaefer 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.[5] The growth of the stock is

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

[4] Although many fisheries have transitioned to limited entry regulation, the restriction is often non-binding. Regulating fishing efficiency also reflects the dominance of biologists on management councils, who may favor solutions that directly limit fishing mortality.

[5] 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 in k) and would reduce tractability of results.

As in the open access model, boats enter in proportion to current individual profits.[6] The price of fish p and costs per unit time per boat c are both constant. The constant of proportionality is δ, which represents entering effort 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 are therefore homogeneous with respect to revenue and costs. Importantly, the quality, or efficiency with which fish are harvested, is assumed to be equal across boats. Relaxing this assumption allows (Johnson & Libecap, 1982) to explore the ability with which heterogeneous fishermen can cohesively lobby for various types of regulation. As we set out to determine the optimal level of efficiency for a regulator who cannot restrict E, we assume homogeneous fishers for model tractability. Johnson and Libecap's conclusion, that fishermen will not effectively lobby for effort controls, is consistent with our assumption. 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 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 without regulation. 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, $\overline{k}$. Here, we abstract from the exact form of regulation and model the regulation as the agency choosing technical efficiency, $k(t) \in [\underline{k}, \overline{k}]$. Note that k can reflect physical technology or restrictions on fishing time—the continuous-time analog to season closures. The captured agency maximizes the present value of future profits to the representative fisher discounted at rate, r, as follows:

[6] We have considered the much more complicated case of allowing rational expectations on the part of entrants. In that case, let $y(t)$ be the present value of profits to a representative fisher discounted to time t. Then $\dot{E} = \delta y$, and we have an additional state equation: $\dot{y} = pkX - c + ry$. This is the case explored by Berck and Perloff (1984). Our preliminary analysis suggests that, like the problem analyzed in this paper, the Hamiltonian is still linear in k, and the same stock size results in equilibrium. However, the short-run dynamics are significantly complicated (as in Berck and Perloff).

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

subject to (1) and (2). The variables E, k, and X 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 $\overline{k}$ 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 the associated interior choice of k.

2.1 The Singular Control

The singular control (where k is interior) is found by first calculating 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

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

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 a singular control,

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

This equation implicitly defines optimal fishing efficiency, from the perspective of the captured regulator. Substituting for $\dot{X}$ and $\dot{E}$ and solving this expression for k^* give 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 singular 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

Setting the time derivative of λ equal to zero and substituting as before from $H_k=0$ yield $f'(X_{ss})=r$, where subscript $_{ss}$ refers to steady state. 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 $\underline{k} < k_{ss} < \overline{k}$, 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 $X = 0$ and $E = 0$ (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.[7] To facilitate this analysis, we make use of Eq. (13), which implicitly describes the optimal fishing efficiency, k^*. After rewriting, Eq. (13) 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 results:

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

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

which 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:

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

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

[7] Adjustment of the costate variables is accounted for in the derivation of k^*. This permits investigation of stability in only two dimensions (as opposed to four).

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:

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

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

This unambiguously gives the signs of the slopes of the nullclines near the steady state as follows:

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

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

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 Fig. 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

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

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 Fig. 1. In the figure, the convergent path 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 is not on the one-dimensional convergent path (given by the dotted line in Fig. 1) at the start? In that case, since H is linear

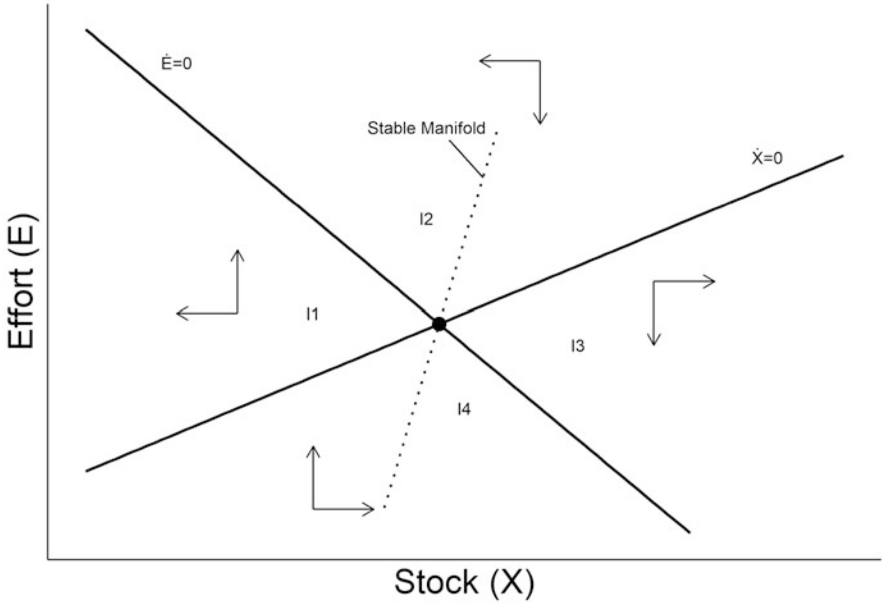

Fig. 1 Phase plane for the captured fishery model in $\{X, E\}$ space with implicit optimal fishing efficiency, $k^*(X, E)$. This is a saddle point equilibrium where the convergent path (stable manifold) is of dimension one with positive slope, represented by the dotted line

in k, k should be set to intersect the convergent path as rapidly as possible. From Eq. (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, $\overline{k}$, to hit the convergent path as quickly as possible.

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

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

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.[8] Comparative statics on the steady state reveal $\frac{dX}{d\tilde{k}} < 0$. 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 low and the stock is high (i.e., to the right of the dotted line in Fig. 1), the regulator should set $k = \overline{k}$. Alternatively, when effort is high and the stock is low (to the left of the dotted line), the regulator should set $k = \underline{k}$. These actions move the system toward 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 (according to Eq. (14)), eventually driving the system to a 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[9] who chooses effort while enjoying the largest possible catchability (efficiency), $\overline{k}$. The sole owner solves

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

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

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

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

where the 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 chooses $\overline{E}$, the highest level of effort possible, if $X < X_{ss}^S$ and chooses $\underline{E}$ 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.

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

[9] 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.

Unlike the captured regulator, the sole owner's solution accounts for all costs. Higher costs are associated with larger optimal stock size for the sole owner, $\frac{\partial X_{ss}^S}{\partial c} > 0$. This is not so for the captured regulator. The inequality in (31) holds because $p\overline{k}X > c$. 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. When effort costs are zero ($c = 0$), 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 $\overline{k} > k_{ss}^*$. 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 imposes lower harvest efficiency than the sole owner.

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

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	$\frac{c}{p\overline{k}}$	$f'(X) = r$ or $x = \frac{c}{pk^*}$	$f'(X) = r - \frac{cf(X)}{X(p\overline{k}X-c)}$
E	$\frac{f(X)p}{c}$ or $\frac{f(X)}{\overline{k}X}$	$\frac{f(X)p}{c}$	$\frac{f(X)}{\overline{k}X}$
k	$\overline{k}$	$\underline{k} < k^* < \overline{k}$	$\overline{k}$

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

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

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 following table.

Parameter	Description	Value
r	Discount rate	0.05
p	Price	30
c	Cost parameter	5
δ	Entry rate (per profit)	0.5
K	Carrying capacity	100
g	Intrinsic growth rate	0.2
$\overline{k}$	Maximum fishing efficiency	0.007
$\underline{k}$	Minimum fishing efficiency	0.0033
$\overline{E}$	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 is devoted to comparing the dynamics of each model starting from each of the two starting states.

As explained above, the sole owner has an objective that is linear in her control: effort. If she finds herself in the $\left\{ {good \atop bad} \right\}$ state, she maximizes rents by setting $\left\{ {\overline{E} \atop \underline{E}} \right\}$, represented by the dotted lines in Fig. 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. Under 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; the dynamics are graphed by the long-dashed path, ending at the downward triangle. On the other hand, if the starting state is good and if $k = \overline{k}$, the short-dashed path is followed, ending with the upward triangle. 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 Fig. 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 $\overline{k}$ for some time and then to adjust k to reach the steady state along the convergent path.[10] In the figure, if the captured regulator starts in the good state, he

[10] 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 performed in R.

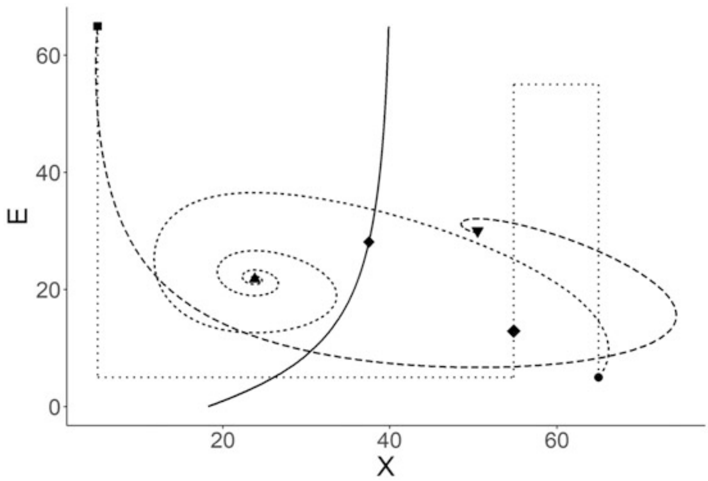

Fig. 2 Dynamics of all three models, starting from "good" (circle) and "bad" (square) states. (1) Starting from either state, the sole owner chooses either $E = \overline{E} = 55$ or $E = \underline{E} = 5$, following the dotted graph to the sole owner steady state given by the diamond. (2) In the open access model, an oscillatory route is followed to steady state. Starting from the "good" state and if $k = \overline{k}$, the open access model moves according to the long-dashed graph, ending at the downward triangle. Starting from the "bad" state and if $k = \underline{k}$, the open access model moves according to the short-dashed graph, ending at the upward triangle. (3) Starting from the "good" state, the captured regulator follows the path of the open access model with $k = \overline{k}$ 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 diamond)

optimally follows the short-dashed line by setting $k = \overline{k}$, following the short-dashed 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 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 quickly that some are eventually driven out by decreases in k along the convergent path.

6 Discussion

While the world's strongly managed fisheries have largely recovered to sustainable levels, declines in poorly managed fisheries continue. This is often loosely attributed to the "tragedy of the commons." We think a more nuanced explanation may be at play. We have studied the problem in which a fishery manager is "captured" by the industry. Such a regulator cannot directly control entry and must therefore achieve management goals by relying on efficiency restrictions (such as technology and season lengths) as his policy instruments. The regulator is captured in the sense that he attempts to maximize the present value of profits to the representative fisher in the industry. This kind of captured regulator is plagued with the unfortunate circumstance where potential entrants look just like incumbents, and the only way to discourage entry is to restrict the efficiency of harvest to drive down profits. In the context of a common, simple fishery management model, we explore the management of such a fishery. The "captured" regulator must trade off the efficiency of harvest against the increased short-term profits of doing so; these profits are dissipated in the long run since entering firms drive down the fish stock. We show that, despite the regulator's goal of maximizing the net present value of harvest to the representative fisher, he unambiguously allows overfishing. The short-run dynamics are derived and a simple example is provided. This may help explain why even "managed" fisheries—those with well-meaning regulators who cannot directly control entry or harvest—may continue to experience overfishing.

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