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The Economics of Illegal Fishing: A Behavioral Model

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Abstract *This paper analyzes the microeconomic behavior of fishers responding to imperfectly enforced regulations through illegal fishing and efforts to avoid detection. An intraseasonal optimization model is analyzed to determine optimal (profit-maximizing) harvesting strategies at the individual fisher level in response to input controls (such as gear or labor usage) or output controls (individual harvest quotas). For each regulatory option, the analysis explores: (a) the manner by which enforcement affects individual decisions concerning fishing and avoidance activity, (b) the level of enforcement necessary to achieve specified conservation goals, and (c) the role of various behavioral parameters in determining fisher decisions. It is shown, in particular, that the nature of avoidance behavior plays a crucial role in determining fisher response to regulations. Broad implications of illegal behavior on the sustainability of fishery systems are also discussed.*

Key words Behavioral models, effort control, fishery management, illegal fishing, individual quotas, noncompliance.

Introduction

Illegal fishing has often played a major role in the failure of fishery regulations and the consequent loss of long-term fishery benefits. This problem, and its roots in the imperfect enforcement of fishery regulations, has been widely noted (*e.g.*, Crutchfield 1979; Copes 1986), yet illegal behavior remains among the least studied aspects of fisheries worldwide (Sutinen and Hennessey 1986). In particular, there has been a lack of attention given, both in policy making and in fisheries economics,

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to the microeconomic behavior of fishers interacting with the regulatory environment (*e.g.*, Wilen 1985; Anderson and Lee 1986; Anderson 1989). This paper focuses on that theme, examining illegal fishing as a behavioral response of self-interested fishers to imperfectly enforced regulations.

The limited literature available on the economic analysis of illegal fishing falls into three groupings: theoretical, empirical, and policy oriented. The first of these typically focuses on studies of optimal fishery enforcement at an industry or sectoral level, with contributions including those of Andersen and Sutinen (1983), Sutinen and Andersen (1985), Milliman (1986), Anderson and Lee (1986), Anderson (1987, 1989), Neher (1990), and Sutinen (1993). A set of reviews on economic theory and modeling of fishery enforcement is contained in Charles (1993), while the compilation of Sutinen and Hennessey (1987) combines discussion of theory with policy aspects. Empirical studies tend to deal with either behavioral responses of fishers to enforcement (*e.g.*, Sutinen and Gauvin 1989; Furlong 1991; Kuperan and Sutinen 1998), or case studies of optimization at a sectoral level (Lepiz and Sutinen 1985; Sutinen 1988), using operations research methods (cf. Armacost 1992; Crowley and Palsson 1992).

The basis of this literature lies in the general economics of crime and punishment, in particular the seminal work of Becker (1968) and Stigler (1971), wherein two fundamental results were established: (*a*) with costly enforcement, it will not be optimal to ensure complete compliance; and (*b*) in such situations, one can expect illegal activity to occur on the basis of marginal returns to individual decision makers responding to a set of regulations and enforcement levels. The latter point, common to most of the literature on illegal fishing, has important moral implications; fisher decisions about whether to fish illegally are assumed to be based solely on profit-maximizing (or utility-maximizing) criteria, with any penalties incurred for illegal fishing being perceived as simply a "cost of doing business."

Within such a scenario, and given that illegal fishing often provides high returns with typically low probabilities of detection and low resulting fines if caught (Kuperan and Sutinen 1998), one would expect illegal activity to be widespread. This does, indeed, seem to be the case in many fisheries. On the other hand, in many other fisheries, the majority of fishers comply with regulations. In the latter case, it seems that nonpecuniary factors, based on moral and social considerations, play a major role in fisher decisions, a point recently established in an important empirical study (Kuperan and Sutinen 1998; Sutinen and Kuperan 1999).

This paper maintains the Becker/Stigler perspective, modeling the microeconomic behavior of profit-maximizing fishers in the face of regulatory restrictions, and in the absence of the above moral and social factors. This scenario is crucial to understand, reflecting the fishery manager's "worst case" scenario, in which there is no inherent deterrence built into the socio-cultural fabric of the fishery. It is also a realistic scenario, since, as Kuperan and Sutinen (1998) note, it is typical for a group of fishers to contain a subgroup of "chronic, flagrant violators... motivated only by the direct tangible consequences of their actions... [for whom] moral obligation and social influence have little or no effect on their behavior." This subgroup of profit-maximizers may well account for the majority of violations, and thus, as Kuperan and Sutinen (1998) argue, deserve emphasis in enforcement efforts.

This paper examines the response of fishers to regulations on inputs (*e.g.*, gear and labor) or on outputs (harvest), and specifically, how fisher behavior interacts with enforcement activity by fishery management. The approach here differs from that of most past studies, focusing on explicit behavioral modeling of fisher-level decisions that underlie industry-level enforcement models (such as those referenced above). Emphasis is placed on modeling not only illegal fishing activity *per se*, but also the avoidance behavior of fishers seeking to evade detection and apprehension, as well as implications of that behavior on the effectiveness of fishery enforcement.

This extends past efforts to examine avoidance behavior, and complements the empirical approach of Kuperan and Sutinen (1998) on the topic.

The illegal fishing model is presented in the next section. Subsequent sections describe the determination of optimality conditions and the generation of specific results. The final section of the paper summarizes the results, and returns to the theme addressed above, examining the implications of moral and social constraints, or the lack thereof, on the sustainability of the fishery management system.

A Model of Fisher Behavior

In this section, a short-run, profit-maximization model is developed of fisher decision making within three regulatory environments: (*i*) unregulated, (*ii*) imperfectly enforced input controls, and (*iii*) imperfectly enforced output controls. The focus is on an intraseasonal analysis of a limited-entry fishery, in which the number of fishers, N; the capital held by each fisher, K; and the initial fish biomass, B, are fixed within a given fishing season. Emphasis is placed on the microeconomic behavior of individual fishers; in most cases, specific values of variables and parameters are assumed to apply to a particular fisher.

Two forms of the model are developed here: (*i*) a general formulation, using generic functional forms; and (*ii*) a linear-quadratic specification of the general case, applying particular assumptions about fishing, avoidance, and enforcement activities.

Fishing Inputs

We assume that each fisher can choose desired quantities of two possible configurations ("input bundles") of variable inputs—in other words, two available "blends" of inputs such as labor, fuel, fishing gear, electronic gear, and fishing location. We assume the two bundles differ in certain clearly specified ways. For example, one bundle may consist of particular electronic gear, labor, and fuel, together with nets of a certain mesh size, while the other bundle could comprise the same electronic gear, labor, and fuel, but with nets of a smaller mesh size. Decisions about fishing activity are then made by choosing quantitative levels (x, x') of the two input bundles.

This assumption facilitates analysis of illegal behavior in that, under input controls, the second of the bundles is assumed to represent illegal fishing (use of an illegal input), so x' is precisely the extent of illegal activity for the given fisher. (In the above example, this may be the amount of time operating with illegal gear; *i.e.*, nets with undersized mesh. Of course with pure output controls, both x and x' are legal input bundles.)

Regulatory Environment

The objective here is to study the fisher's optimal behavior in response to given, but imperfectly enforced, regulations. This behavior is reflected in the fisher's choice of levels of the fishing input bundles x and x', as well as another possible input, the level of "avoidance" activity, A, that could be applied by the fisher seeking to avoid detection or apprehension for illegal fishing. We examine three regulatory environments:

1. *Unregulated*. If there is a complete absence of regulation (apart from limited entry restrictions), both inputs x and x' are legal, and the fisher must then decide, based on the usual profit-maximizing rules, how much of each input to use.

2. *Input Controls*. If a regulatory constraint is placed on inputs, we assume x and x' are the amounts the fisher uses of the legal and illegal input bundles, respectively. (The latter could involve an illegal mesh size, fishing in a closed area, *etc*.).

3. *Output Controls*. As noted above, if the regulatory constraint is placed on output (through catch quotas), harvesting can take place with any levels of x and x', but an illegal harvest $h' = h - \bar{h}$ occurs if the catch (h) exceeds the fisher's fixed allowable quota ($\bar{h}$). We assume quotas are nontransferable, so it is likely that $h' \geq 0$ (*i.e.*, $h \geq \bar{h}$), but the analysis also holds if the catch is less than the quota ($h < \bar{h}$).[1]

Production Function

The fisher's harvest level, h, is given by the short-run production function:

$$h = h(x, x', A; K, B) \qquad (1)$$

where x, x', and A are the levels of the variable inputs, K is the fisher's capital stock (vessel, gear, *etc*.), and B is the biomass of fish available. Typically, the harvest h increases with x, x', K, and B, but $h_A \leq 0$ since avoidance may decrease the time available for fishing and the effectiveness of a unit of fishing input.

In the linear-quadratic specification, it is assumed further that production is: (*i*) linear and separable in the two input bundles x and x', (*ii*) proportional to stock biomass B, and (*iii*) unaffected by the capital stock, K, or the avoidance activity, A. The latter, which is assumed for ease of analysis, means that any detrimental impact of avoidance on production is assumed to be captured in the cost function rather than entering into the production function directly (*i.e.*, $h_A = 0$). Then, the nominal harvests produced from inputs x and x' are qxB and $q'x'B$, respectively (with q and q' constant catchability coefficients), and the individual fisher's production function becomes:

$$h = qxB + q'x'B \qquad (2)$$

Fishing Costs

It is assumed that the total variable cost is given by the sum of cost functions for each input (x, x', and A):

$$\text{Total Variable Costs} = c(x) + c'(x') + c^A(A) \qquad (3)$$

In the linear-quadratic specification, cost functions are assumed to be quadratic, reflecting increasing marginal costs arising due to the aggregation of inputs in "bundles" as well as the common occurrence in fisheries of constrained access to factor markets and inflexible labor markets (due perhaps to contracting or share systems). Specifically, the overall cost function is given by:[2]

$$\text{Total Variable Costs} = cx^2 + c'x'^2 + c^A A^2 \qquad (4)$$

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[1] Optimal quota allocation, the subject of an extensive literature, is not addressed here so as to better focus on operational matters of how a given set of input or output regulations interacts with fisher behavior.

[2] Note that this specification differs from the commonly assumed cubic total variable cost function (and corresponding U-shaped marginal and average cost curves). The single-term form of the quadratic function used here also restricts the total variable cost to the rising portion of a U-shaped curve, implying a linearly increasing marginal cost and avoiding the need to deal with a range of inputs over which total variable costs fall as inputs rise.

Penalties for Illegal Fishing

Following Sutinen and Andersen (1985) and Becker (1968), it is assumed that under regulation, the fisher has the option of fishing illegally, but faces a probability θ of being caught and convicted if doing so. This probability is assumed to increase with the levels of enforcement and of illegal fishing, but to decrease with avoidance activity. Defining E_I and E_o as the levels of enforcement in place under a system of input controls or output controls, respectively, the probability that the fisher will be caught and convicted for fishing illegally is as follows:

$$\theta = \theta(x', E_I, A) \text{ with } \partial\theta/\partial x' \geq 0,\ \partial\theta/\partial E > 0,\ \partial\theta/\partial A < 0;\ \theta \equiv 0 \text{ if } x' = 0 \tag{5a}$$

$$\theta = \theta(h', E_o, A) \text{ with } \partial\theta/\partial h' \geq 0,\ \partial\theta/\partial E > 0,\ \partial\theta/\partial A < 0;\ \theta \equiv 0 \text{ if } h \leq \bar{h} \tag{5b}$$

for the cases of input and output controls, respectively.

It is assumed that, if caught and convicted, the fisher is assessed a fine, which may be constant or may rise with the level of illegal activity. In the latter case, to avoid dealing with an unrealistically large fine, it is assumed that the fine does not exceed the fisher's assets, proxied here by the capital stock, K. [This contrasts with a theoretically "ideal" enforcement policy that equates the fine's expected value to the social opportunity cost of illegal behavior at the margin; see Becker (1968) and Posner (1977)]. The resulting fines for input and output controls, respectively, are then given by:

$$F = F(x'; K) \text{ with } \partial F/\partial x' \geq 0;\ F \equiv 0 \text{ if } x' = 0 \tag{6a}$$

$$F = F(h'; K) \text{ with } \partial F/\partial h' \geq 0;\ F \equiv 0 \text{ if } h \leq \bar{h} \tag{6b}$$

The expected value of the fine is given by the product of the probability and the fine itself, namely θF.

For the linear-quadratic case, this general structure will be considerably simplified through three substantial assumptions: (*i*) in the absence of avoidance, the probability of detection and conviction resulting from a given level of illegal fishing is jointly proportional to the enforcement effort, E_I or E_o, and the level of illegal fishing, x' or h'; (*ii*) avoidance activity, A, reduces the above probability by a factor $(1 - \gamma A)$ where γ is a constant; and (*iii*) the resulting fine on conviction is constant, independent of the extent of illegal activity. (This clearly restrictive assumption, which is applied only to the linear-quadratic case, is adopted primarily to maintain a quadratic model structure, although it is also compatible with the use in some jurisdictions of a "zero tolerance" approach to enforcement.)

With these assumptions, and after suitably scaling the variables, the expected value of the fine in the linear-quadratic case is:

$$\text{Expected Fine} = \theta F = \begin{cases} (1 - \gamma A)E_I x': & \text{input control} \\ (1 - \gamma A)E_o h': & \text{output control} \end{cases} \tag{7}$$

where proportionality constants are set to unity, so enforcement efforts E_I and E_o can also be viewed as expected fines per unit of illegal activity, in the absence of avoidance activity ($A = 0$).

Fisher Optimization

Each year, the fisher must choose a fishing strategy based on desired levels of the inputs x, x', and A. If faced with moral or social constraints, there may be a nonpecuniary aversion to illegal behavior, and thus the very decision to engage in such behavior (*i.e.*, to choose a nonzero value of x' or h') may need to be considered separately (as in the approach of Sutinen 1993; Kuperan and Sutinen 1998). In the present case, however, the fisher is assumed to treat illegal inputs no differently from legal inputs; the goal of the fisher is simply to choose input levels x, x', and A to maximize short-run restricted profits. (Note that this assumes risk-neutrality, and an absence of rent-seeking behavior—costs are not incurred specifically in an effort to have the regulations changed.)

Given the above schedule of probabilities and fines, the single-year optimization problem for the fisher is given by:

$$\max_{x,x',A} [ph(x, x', A; K, B) - c(x) - c'(x') - c^A(A) - \theta F] \tag{8}$$

where x and x' are the amounts of the two input bundles, and p is the unit price of output (assumed parametric to the fisher). Note that inherent in expression (8) is the choice of whether or not to engage in illegal behavior: a value $x' = 0$ (in the case of input control) or a combination of x and x' giving $h' = 0$ (in the case of output control) are valid solutions of this decision problem. On the other hand, if the fisher does undertake illegal fishing, the expected fine for illegal fishing (θF) and the cost of avoidance, $c^A(A)$, are additional costs that may be incurred.

In the linear-quadratic specification, the fisher's annual decision problem for input or output controls, respectively, is:

$$\max_{x,x',A} [pqBx + pq'Bx' - cx^2 - c'x'^2 - c^A A^2 - (1 - \gamma A)E_I x'] \tag{9a}$$

$$\max_{x,x',A} [pqBx + pq'Bx' - cx^2 - c'x'^2 - c^A A^2 - (1 - \gamma A)E_o h'] \tag{9b}$$

Note that these expressions differ only in the variables denoting illegal activity (x' vs. h') and enforcement effort (E_I vs. E_o).

Profit-Maximizing Decision Making

This section derives expressions for optimal fisher behavior for each of the general and linear-quadratic forms of the model, and for each of the three regulatory options: (*i*) no regulation, (*ii*) input controls, and (*iii*) output controls.

Fisher Behavior With No Regulation

In the absence of regulation, there is a zero probability of incurring penalties for illegal fishing ($\theta F = 0$), and no need for avoidance, so $A = 0$ and $c^A(A) = 0$ in the optimization expression (8). Assuming an interior solution of equation (8), with positive values of x and x', the first-order conditions equate value of the marginal product and marginal factor cost for each variable input:

$$ph_x = c_x(x) \tag{10a}$$

$$ph_{x'} = c'_{x'}(x') \tag{10b}$$

where, in this case and other analyses of the general model as specified below, subscripts denote partial derivatives. In the linear-quadratic case, equations (10a) and (10b) become:

$$pqB = 2cx \tag{11a}$$

$$pq'B = 2c'x' \tag{11b}$$

Fisher Behavior Under Input Regulations

Here, illegal behavior arises through use of the input x' (versus the legal x) subject to some probability of being caught and convicted if so engaged. Assuming, as above, that θ and F are functions of x', and again letting subscripts indicate partial derivatives, the first-order conditions are as follows:

$$ph_x \leq c_x(x) \qquad \text{with equality if } x > 0 \tag{12a}$$

$$ph_{x'} - (\theta_{x'}F + \theta F_{x'}) \leq c'_{x'}(x') \qquad \text{with equality if } x' > 0 \tag{12b}$$

$$-\theta_A F = c_A^A(A) - ph_A \tag{12c}$$

where the inequalities are technical requirements to allow for the possibility of a zero input, whether legal ($x = 0$) or illegal ($x' = 0$).

Note that from equation (12a), the optimal level of the legal input, x, is determined as in the case of no regulation [see equation (10a)]. In contrast, the optimal illegal input, x', is determined from equation (12b) by equating its marginal value to the sum of the marginal factor cost and the marginal expected fine. Finally, in equation (12c), the optimal level of avoidance is determined by equating the marginal benefit of avoidance in reducing the expected fine ($-\theta_A F$) to the marginal cost of avoidance $c_A^A(A)$, plus an indirect marginal cost, the lost harvest revenue due to fishing suboptimally ($-ph_A$).

For the linear-quadratic specification (assuming an interior solution with positive values of x, x', and A), equation (12) becomes:

$$pqB = 2cx \tag{13a}$$

$$pq'B - (1 - \gamma A)E_I = 2c'x' \tag{13b}$$

$$\gamma E_I x' = 2c^A A \tag{13c}$$

The left-hand sides of equations (13a) and (13b) are the values of the marginal revenue product with respect to x and x'. For the illegal input x', this is net of the expected fine due to illegal fishing, which increases with enforcement, E_I, and decreases with avoidance, A. The marginal gain and cost of avoidance are equated in equation (13c) to give $A = (\gamma/2c^A)E_I x'$, which is jointly proportional to the levels of illegal input (x') and of enforcement effort (E_I). Note that for any given x' and E_I, avoidance increases with its effectiveness (γ) and decreases with its cost (c^A).

Solving the equations in (13) simultaneously gives the optimal fishing and avoidance inputs:

$$x = pqB/2c \tag{14a}$$

$$x' = \frac{(2c^A)(pq'B - E_I)}{(4c'c^A - \gamma^2 E_I^2)} \tag{14b}$$

$$A = \frac{(\gamma E_I)(pq'B - E_I)}{(4c'c^A - \gamma^2 E_I^2)}. \tag{14c}$$

These expressions are valid given an interior maximum, which occurs if three conditions are satisfied. First, the denominator in equations (14b) and (14c) needs to be positive; this is a mathematical requirement for an interior maximum derived by treating equation (9a) as a function of x' and A. Second, given this, the numerator in equations (14b) and (14c) should also be positive, to ensure positive inputs. Finally, the solution of equation (14c) needs to satisfy the logical model requirement that $1 - \gamma A > 0$. These conditions for an interior maximum can be written:

$$E_I < (4c'c^A/\gamma^2)^{1/2} \tag{15a}$$

$$E_I < pq'B \tag{15b}$$

$$E_I < (c^A/\gamma^2)(4c'/pq'B). \tag{15c}$$

The analysis below focuses on interior solutions, as in equation (14), for which conditions in equation (15) hold. Note that from equation (15), illegal fishing will occur ($x' > 0$) only if enforcement effort is not so high as to remove the incentive to do so. Furthermore, note that the parameter (c^A/γ^2) plays a major role; illegal activity can occur even at high enforcement levels, if avoidance is expensive (high c^A) and/or relatively ineffective (low γ^2). This parameter is examined further at a later point.

Fisher Behavior Under Output Regulations

When output, rather than input, is regulated, the fisher's optimization problem remains as in equation (8), except that now both input bundles are legal, and illegal fishing occurs when the fisher's total catch exceeds the (predetermined) individual catch quota, $\bar{h}$. The profit-maximizing, first-order conditions (with subscripts indicating partial derivatives) are:

$$\left[p - (\theta_{h'}F + \theta F_{h'})\right]h_x \le c_x(x) \text{ with equality if } h' > 0 \tag{16a}$$

$$\left[p - (\theta_{h'}F + \theta F_{h'})\right]h_{x'} \le c_{x'}(x') \text{ with equality if } h' > 0 \tag{16b}$$

$$-\theta_A F = c_A^A(A) - ph_A \tag{16c}$$

Expressions (16a) and (16b) are similar to their counterparts in the absence of regulation [equations (10a) and (10b)], except that for harvesting beyond the legal quota, fisher decisions are based on an effective price given by the actual price, p, minus the marginal expected fine (marginal with respect to the illegal harvest h').

With the linear-quadratic form, equations (16a), (16b), and (16c) for optimal inputs x, x', and A under harvest controls (assuming an interior solution with $h' = h - \bar{h} > 0$ and positive input levels) become:

$$\left[p - (1 - \gamma A)E_o\right]qB = 2cx \tag{17a}$$

$$\left[p - (1 - \gamma A)E_o\right]q'B = 2c'x' \tag{17b}$$

$$\gamma E_o(qxB + q'x'B - \bar{h}) = 2c^A A \tag{17c}$$

Here the optimality conditions for x and x' are symmetric, differing only due to differences in catchabilities (q versus q') and input costs (c versus c'). Note also that the left-hand side of equation (17c), the marginal benefit of avoidance, can be written $\gamma E_o h'$ so the optimal avoidance effort is $A = (\gamma/2c^A)E_o h'$. As for input controls, the latter is jointly proportional to the illegal activity (now h') and enforcement effort (E_o). Furthermore, for given levels of these variables, the desired avoidance increases with its effectiveness (γ) and decreases with its cost (c^A).

Now, to solve equations (17a), (17b), and (17c), it is convenient to first examine harvests in the absence of enforcement. Setting $E_o = 0$ in equations (17a) and (17b) provides the optimal inputs x and x' in such a case. Substituting these in equation (2) gives the fisher's desired total harvest given zero enforcement: $h_M = (pq^2B^2/2c) + (pq'^2B^2/2c')$. (For later use, we designate the first term here as h_L and the second as h_I; under input controls, these are the maximum legal and illegal harvests, respectively.) Then the solution to the three equations in (17) for optimal values of the decision variables x, x', and A can be written:

$$x = (pqB/2c)\,\frac{\left[p - E_o - (\gamma^2 E_o^2/2c^A)\bar{h}\right]}{\left[p - (\gamma^2 E_o^2/2c^A)h_M\right]} \tag{18a}$$

$$x' = (pq'B/2c')\,\frac{\left[p - E_o - (\gamma^2 E_o^2/2c^A)\bar{h}\right]}{\left[p - (\gamma^2 E_o^2/2c^A)h_M\right]} \tag{18b}$$

$$A = \frac{(\gamma E_o/2c^A)\left[(p - E_o)h_M - p\bar{h}\right]}{\left[p - (\gamma^2 E_o^2/2c^A)h_M\right]}\,. \tag{18c}$$

These equations for x, x', and A are valid given an interior solution. This requires logically that $A > 0$ and $h' > 0$, but since h' and A are proportional from equation (17c), it is sufficient to show that $A > 0$, which, in turn, requires the numerator and denominator in equation (18c) be positive. It is also necessary that $1 - \gamma A > 0$ by assumption in the model. Thus, an interior solution will be obtained if:

$$E_o < p\,(h_M - \bar{h})/h_M \tag{19a}$$

$$E_o < (2c^A p/\gamma^2 h_M)^{1/2} \tag{19b}$$

$$E_o < 2\,(c^A/\gamma^2)/(h_M - \bar{h})\,. \tag{19c}$$

As with input controls, these conditions imply that illegal fishing will occur ($x' > 0$) only if enforcement effort does not totally remove the incentive to do so. Again, the parameter (c^A/γ^2) is important here, with the relationship between illegal activity and enforcement dependent on the cost and effectiveness of avoidance. Note that in the following, model parameters are assumed to be such that an interior solution does indeed occur.

Analysis

Two fundamental themes are analyzed in this section: (*i*) the nature of interactions between enforcement and fisher response, with implications for the effectiveness of input and output controls; and (*ii*) the determination of enforcement levels required to achieve specified conservation targets (harvest levels) under each form of regulatory control.

Impacts of Enforcement

Enforcement (E_I and E_o) acts through the regulatory environment of detection (θ) and fines (F) to affect fishing and avoidance activities (x, x', and A). These impacts are determined implicitly through the first-order conditions in equations (12), (13), (16), and (17), and explicitly through the results in equations (14) and (18). The following focuses on the case of most interest, in which a positive level of illegal fishing is profitable from the fisher's perspective, making all first-order conditions into equations.

As noted earlier, in the absence of enforcement ($E = 0$), there is no risk that violations will be detected ($\theta = 0$), so fishers will choose not to engage in avoidance activity ($A = 0$). Under such conditions, all sets of first-order conditions collapse to the optimality criteria that apply in the absence of regulation. In other words, whatever the set of regulations, there is absolutely no effect on fisher behavior if those regulations are not enforced (assuming an absence of moral considerations).

With a positive level of enforcement, on the other hand, the fisher's response to enforcement varies with the form of controls in place. Furthermore, examination of results in the previous section indicates that the nature of this difference cannot be deduced in a clear-cut manner in the general case or the specific linear-quadratic model. Not only do optimality conditions differ structurally between regulatory options, more fundamentally so do the units of measurement, both with respect to fishing variables (x, x', vs. h') and enforcement variables (E_I vs. E_o).[3]

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[3] Indeed, even for a single form of regulation, parameters such as detection probabilities and the effectiveness of avoidance will vary across the many possible regulatory violations. For example, a fisher might violate output controls by dumping or highgrading (to improve the mix of species or sizes in the catch) or by landing fish in excess of the allowable quota. The former, occurring at sea, is likely much more difficult to detect than the latter.

These factors suggest that, within a theoretical analysis, one cannot draw general conclusions about the relative merits of input or output controls as regulatory tools. Ultimately, comparison of these options must be done empirically, possibly based on models such as those presented here.[4]

It is possible, however, to compare qualitatively the impacts of enforcement on illegal fishing. Our analysis indicates that such impacts depend strongly on the nature of avoidance activity; specifically, its cost and effectiveness. “Regular” interaction of enforcement with fisher behavior occurs if avoidance is neither too cheap nor too effective, satisfying the following conditions:

$$\text{Input controls: } (c^A/\gamma^2) > (pq'B)^2/4c' \tag{20a}$$

$$\text{Output controls: } (c^A/\gamma^2) > p(h_M - \bar{h})^2/2h_M \tag{20b}$$

Given these conditions, with input controls, the illegal input, x', decreases steadily with the level of enforcement, E_I (while the optimal level of the legal input, x, is independent of enforcement and avoidance). Similarly, with output controls (and assuming the presence of illegal harvests, $h > \bar{h}$), both inputs x and x' decrease steadily with the level of enforcement, E_o.

These results imply, first, that for “regular” avoidance parameters, the fishery manager can reduce illegal fishing toward zero by increasing enforcement toward the upper limits $E_I = pq'B$ under input controls, or $E_o = p(h_M - \bar{h})/h_M$ under output controls. Second, at low levels of enforcement, fishers will respond to increases in enforcement by increasing avoidance activity, but at higher enforcement levels, it becomes uneconomical to continue to do so, at which point avoidance actually decreases with enforcement.

On the other hand, if the above conditions on avoidance do not hold, so that avoidance is very inexpensive and/or very efficient, then the fisher response to enforcement will be different. The optimal level of avoidance will then increase indefinitely with increasing enforcement; the fishers react to enforcement not necessarily by reducing illegal behavior, but more so by attempting to avoid apprehension. This very different response highlights the importance of understanding avoidance behavior, since changes in key avoidance parameters can have a major impact on the effects of enforcement activities.

Enforcement Requirements to Achieve Conservation

Suppose that, for conservation reasons, fishery management seeks to set a suitable enforcement level to limit the aggregate harvest to a certain total allowable catch (TAC). The realized aggregate harvest is given by the sum across the N fishers of all individual harvests, h. The latter are obtained for the case of input controls by inserting expressions for x and x' from equation (14) into the production function $h = qBx + q'Bx'$, and for output controls by combining equations (17c) and (18c):

$$\text{Input control: } \quad h = h_L + \frac{q'B(pq'B - E_I)}{(2c' - \gamma^2 E_I^2/2c^A)} \tag{21a}$$

[4] The option also exists to combine the use of input and output controls within a single regulatory regime. This is not uncommon in practice, although one or the other tends to dominate. Conservation implications of fully combining the two regulatory approaches were examined recently by Canada’s Fisheries Resource Conservation Council (1996). Economic aspects could be examined through a modified version of the model in this paper.

$$\text{Output control} \quad h = \bar{h} + \frac{\left[p(h_M - \bar{h}) - E_o h_M\right]}{\left[p - (\gamma^2 E_o^2 / 2c^A) h_M\right]} \tag{21b}$$

with $h_L = pq^2B^2/2c$ and $h_M = h_L + h_I$ (with $h_I = pq'^2B^2/2c'$) as above.

In general, these individual harvests will vary among fishers, but suppose, for simplicity, that all N fishers are identical. Then, to keep within the overall TAC, the manager should maintain the actual per-capita harvest at a level $h^* = \text{TAC}/N$.[5]

Note that under input controls, each fisher will catch at least h_L, the harvest arising from use of the legal input, but will not wish to catch more than h_M, the "unregulated" total harvest. Thus, the range of values of h^* that can be feasibly considered is $h_L < h^* < h_M$.

With output controls, the situation is more complicated due to interactions between the per-capita catch, h^*, that the manager wishes to achieve, and what the manager declares to be the fisher's allowable quota, $\bar{h}$. In the absence of illegal fishing, the manager would simply set the latter equal to the former ($\bar{h} = h^*$). However, with illegal activity as an available option, the actual catch is likely to exceed the legal quota, $\bar{h}$. Thus, to avoid overharvesting, the manager must set the legal quota below the acceptable catch; *i.e.*, $\bar{h} \le h^*$. Here it is assumed that this is the case, so under output controls, the feasible range of values of h^* is $\bar{h} \le h^* \le h_M$ (assuming $\bar{h}$ is at least h_L).[6]

Equating expressions (21) for the actual per-capita harvest, h, to the desired level, h^*, and rearranging, we obtain quadratic expressions for the enforcement effort required to achieve the desired conservation target under each form of control:

$$\text{Input:} \quad (\gamma^2/2c^A)(h^* - h_L)E_I^2 - (q'B)E_I + 2c'(h_M - h^*) = 0 \tag{22a}$$

$$\text{Output:} \quad (\gamma^2/2c^A)(h^* - \bar{h})E_o^2 - E_o + p(h_M - h^*)/h_M = 0. \tag{22b}$$

It can be shown that, for any level of the target catch, h^*, that is feasible (as defined above), a solution to each equation exists, as long as avoidance is "regular" in that the conditions in equations (20a) or (20b) hold. In such cases, for any feasible h^*, there will be two positive solutions for the required enforcement effort, but only the lower of the two satisfies the conditions on enforcement in equations (15) and (19). Using this solution, the required enforcement effort under input and output controls is as follows:

$$E_I = \frac{(q'B)c^A}{(h^* - h_L)\gamma^2}\left\{1 - \left[1 - (2p/h_I)(\gamma^2/c^A)(h^* - h_L)(h_M - h^*)\right]^{1/2}\right\} \tag{23a}$$

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[5] Since earlier results were based on assuming a positive level of illegal activity, the additional assumption of identical fishers implies that everyone is fishing illegally. In the present context, this should not be taken literally (in which case every fisher could immediately be apprehended), but rather as exacerbating the "worst-case" nature of the analysis. Nevertheless, in practice, the proportion of fishers fishing illegally is an important matter. For example, at a set level of enforcement, the greater this proportion, the greater the probability that a monitored fisher is engaged in illegal activity, but the lower the probability that a given fisher is among those monitored (a point similar to the rationale for why fish move in schools). However, such matters are beyond the scope of this paper.

[6] As noted above, this could have moral implications, particularly in legitimizing the existence of illegal harvesting, which, in turn, could affect the long-run sustainability of the regulatory system. This is discussed in more detail below.

$$E_o = \frac{c^A}{(h^* - \bar{h})\gamma^2}\left\{1 - \left[1 - (2p/h_M)(\gamma^2/c^A)(h^* - \bar{h})(h_M - h^*)\right]^{1/2}\right\} \qquad (23b)$$

Analysis of these expressions shows that required levels of enforcement under both forms of regulation (E_I and E_o) decrease with increases in the TAC quota (and, thus the individual harvest, h^*, targeted by the manager). Specifically, the required level of enforcement decreases from high levels (necessary when the harvest is to be kept close to minimal levels, h_L or $\bar{h}$) toward zero (as harvest is allowed to rise toward its unregulated level h_M). This intuitive result, derived from the present fisher-level behavioral model, is in keeping with the assumed form of enforcement costs used in a fishery-level optimization context (Sutinen and Andersen 1985; Sutinen 1993).

Furthermore, it may be noted that, assuming $x' > 0$, both E_I and E_o decrease as avoidance becomes more expensive and/or less efficient. To summarize, less fishery enforcement is required if: (*i*) fishers have less incentive to overfish (high h^*), and/or (*ii*) fishers have less incentive to avoid fishery enforcement measures (high c^A or low γ^2).[7]

Discussion

This paper has focused on microeconomic decision making of individual fishers with the option to fish illegally within an environment of imperfect regulatory enforcement. A unified model was developed, analyzing illegal fishing behavior under either input or output regulations. The model emphasizes the fisher's intraseasonal decision problem, since, in practice, it is within this timeframe that decisions about illegal fishing are made.

The model could be applied to specific case studies, given suitable empirical data. However, as a theoretical model, its principal benefit lies in the insights provided into interactions between fishing, enforcement, and avoidance.

Summary

Under the assumption of simple, profit-maximizing behavior, the present analysis is compatible with past studies, indicating how illegal fishing (exceeding quotas or using illegal gear) can occur if the marginal value of the catch, net of the expected marginal fine, exceeds the marginal factor cost. Analysis of the model has produced a number of results, summarized below:

1. The choice between input and output controls in fishery management is an empirical matter, since, from a theoretical perspective, universal conclusions cannot be drawn about the relative merits of the two forms of management.

2. Illegal fishing will occur ($x' > 0$ or $h' > 0$) only if enforcement effort is not so high as to remove the incentive to do so, and if the effectiveness of avoidance is not too great, nor its cost too low. Avoidance effort will occur at a level jointly

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[7] It should be noted that if avoidance is either very inexpensive or very efficient, so the conditions in expressions (20a) and (20b) do not hold, then there will be some otherwise-feasible h^* values that cannot be achieved, regardless of the enforcement level. This limitation on the capabilities of enforcement arises due to the high impact of avoidance activity in such circumstances.

proportional to the extent of illegal activity and of enforcement; for given levels of the latter, the desired avoidance effort increases with its effectiveness (γ) and decreases with its cost (c^A).

3. Understanding avoidance behavior appears to be crucial to any efforts to improve fishery enforcement. How enforcement and fisher behavior interact depends strongly on characteristics of avoidance, specifically its cost and effectiveness. When avoidance is neither too cheap nor too effective, the interaction is regular. In this case, at low levels of enforcement, fishers respond to increases in enforcement by increasing avoidance, but at higher enforcement levels, it becomes uneconomical to continue to do so, and avoidance decreases with enforcement. Overall, illegal activity decreases steadily with enforcement, so the fishery manager is able, in theory, to reduce illegal fishing toward zero by increasing enforcement. If, however, avoidance is very inexpensive and/or very efficient, then the optimal level of avoidance will increase indefinitely with increasing enforcement; fishers react to enforcement not so much by reducing illegal behavior as by focusing on avoiding apprehension.

4. Less fishery enforcement is required if fishers have less incentive to overfish (because the TAC is large), and/or fishers have less incentive to avoid fishery enforcement measures (since avoidance is costly or inefficient).

Intertemporal Aspects

This model also can be used as a module within intertemporal models of optimal fishery enforcement. Such models (*e.g.*, Sutinen and Andersen 1985, Sutinen 1993) involve the choice of decision rules for setting enforcement effort $\{E_t\}$ and a set of input or output controls to maximize the discounted present value of a stream of net benefits given specified fish population dynamics. This model permits the calculation of total annual net benefits from the fishery in each year, t, for a given enforcement effort, E_t, and regulatory package of input or output controls, by first predicting fisher response in terms of input levels x, x', and A, and then aggregating over all fishers. Thus, this microeconomic analysis of illegal fishing behavior leads not only to a better understanding of fisher response to regulations, but also to a mechanism for basing industry-level analysis of optimal enforcement on detailed microeconomic response functions.

Moral and Social Aspects

As noted previously, a crucial underlying issue in addressing illegal fishing behavior lies in the determinants of that behavior; in particular, the presence or absence of moral and social considerations. This paper focused on exploring a worst-case scenario of amoral profit maximizing by fishers, in which decisions about fishing illegally are made merely by balancing expected revenues and costs, and possible penalties for illegal fishing are simply "costs of doing business." This situation has implications for sustainability of the fishery management system.

In such a case, the manager is faced with the dilemma discussed earlier. Suppose the manager simply sets the allowable quota or effort at what has been determined as the desired level ($\bar{h} = h^*$). If there were no illegal fishing, this action would produce "correct" overall exploitation levels. However, with illegal fishing, allowable levels will be exceeded, and over harvesting will occur—as has been observed in the past.

The alternative is to set the declared allowable catch or effort at a suitably reduced level ($\bar{h} < h^*$). This would keep actual harvests, including illegal catches, within desired limits. There is, however, a risk involved, namely that illegal behavior could be institutionalized, or be perceived to be legitimized.

Suppose the management agency systematically reduces the TAC to account for estimated illegal catches. On the one hand, this creates an incentive to report violators; by reducing illegal fishing, the legal TAC can be increased. However, this practice also penalizes law-abiding fishers—their catch is reduced—while violators obtain not only a share of the reduced TAC, but also an illegal catch. An incentive is created to join the violators, fueled perhaps by a sense that the management agency is willing to accept illegal fishing, having incorporated it into the decision-making process. In either case, there may be a loss of faith in the management process, leading to increased illegal fishing.

Whether or not the institutional dilemma inherent in this "worst-case" scenario needs to be taken into account is very much an empirical matter. It may be important to contrast fisheries where illegal activity is so widespread as to be considered the norm, with those where such behavior is almost universally rejected as antisocial—where breaking the law is not acceptable practice. In between there are many intermediate cases in which the majority of fishers comply with regulations, while some do not.

Situations in which moral and social factors play a role in limiting illegal fishing can be partially addressed using the present model, by incorporating into the fisher's optimization function a cost of illegal fishing in addition to the expected fine, to reflect the intrinsic moral disbenefit of such activity. Alternatively, this can be dealt with more explicitly; Kuperan and Sutinen (1998) and Sutinen and Kuperan (1999) extend the traditional enforcement model to incorporate moral and social variables, as well as economic ones, into the fisher's decision problem. Application of this extended model to a specific fishery produced empirical evidence showing the extent to which moral and social considerations (*e.g.*, relating to the perceived legitimacy of regulations) impact the decision making of fishers.

Clearly, there remains much scope for further research on illegal fishing behavior and fishery enforcement. In particular, the analysis in this paper points to the specific need for more extensive studies of avoidance behavior by fishers, since in the scenario addressed here, such behavior can play a major role in determining the impact of enforcement effort.

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