OPTIMAL DYNAMIC FISHERIES ENFORCEMENT

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ABSTRACT

It has been established that the path of a fishery over time, i.e. stocks, fleets, effort and profits, depends *inter alia* on the enforcement of the fisheries management rules in place. It has further been established that optimal enforcement of fisheries management rules depends *inter alia* on the shadow value of biomass at each point of time. This raises the question of the optimal path of fisheries enforcement over time. Given a certain state of the fishery, a fisheries management system, enforcement tools and a penalty structure, what would be the optimal enforcement effort over time?

This paper deals with this issue. Given the above constraints, it attempts to solve the dynamic problem of optimal enforcement of the fisheries rules over time. Not surprisingly, it turns out that the optimal enforcement effort should definitely not be constant. On the contrary, given the other parameters of the problem, optimal enforcement is generally a function of the state of the fish stocks at each point of time. In fact, it appears that the optimal enforcement effort should be a monotonically declining function of the fish stocks (provided a sustainable fishery is optimal).

A related issue is the target harvest that may be set under the fisheries management system. The optimal path of this over time and its interaction with optimal enforcement is also explored.

Keywords: Fisheries enforcement, dynamic fisheries enforcement, optimal fisheries dynamics

INTRODUCTION

Fisheries management consists of two components; (i) a fisheries management system and (ii) the enforcement of the system. The fisheries management system is essentially a set of rules as to how fishing may proceed. The role of fisheries enforcement is to ensure that the fishery complies with these rules, i.e. proceeds in accordance with the fisheries management system.

Both components are of course crucial for fisheries management. Clearly, without a fisheries management system (formal or informal) there is nothing to enforce and there can be no fisheries management. Wit a fisheries management system, but no enforcement of the rules, the fishery will simply proceed in the individually preferred way as if there was no fisheries management.

It is important to recognize that with a fisheries management system in place and the management measures (e.g. the TAC etc.) set, the actual fisheries management that takes place consists of the fisheries enforcement activity. The fisheries management system and fisheries management measures are just words on paper. The real fisheries management is the fisheries enforcement!

In this paper we begin by summarizing the fisheries enforcement theory outlined in [1] and discussed in more detail in the report of the COBECOS project [2]. In this basic enforcement theory, the shadow value of biomass, denoted by λ, is taken as exogenous. This, while formally correct and certainly appropriate as a rule for the enforcement activity at a point of time (provided the correct λ is used), is not entirely satisfactory for planning purposes and in the dynamic context more generally. The shadow value of biomass is an endogenous variable and depends inter alia on the enforcement policy. Thus, when a change in enforcement effort is contemplated there will be a consequent change in λ. To account for this and to provide a basis for long term planning of the enforcement activity, the assumption of an exogenous shadow value of biomass is relaxed and the resultant optimal dynamic enforcement policy derived.

It turns out that the optimal dynamic enforcement policy is in general fairly complicated and it appears to be difficult, possibly impossible, to obtain explicit functions for the enforcement efforts or characterize its optimal paths in general. Therefore, to illustrate the nature of these paths, a numerical fisheries enforcement model is constructed and the approximately optimal enforcement paths for this model derived and discussed.

MODELLING PRELIMINARIES

To allow us to focus on essentials, we model a very simple fisheries enforcement situation. Extension to more complicated and, possibly, more realistic situations is straight-forward.

Fishers are assumed to gain private benefits from fishing defined by the benefit function:

$$B(q,x)$$

This function is taken to be monotonically increasing in biomass, x, with a unique maximum in the volume of harvest, q, and concave. To make the model economically interesting, $B(q,x)>0$ for some biologically reasonable x and a positive q.

The social (or collective) benefits from fishing differ from the private benefits it that the shadow value of any biomass changes affected by harvest must be subtracted from the private benefits. Write this as:

$$B(q,x)-\lambda\cdot q+\lambda\cdot G(x),$$

where λ represents the shadow value of biomass and $G(x)$ the biomass growth function. Note that at a point of time, both λ and x, is given, so. The term $\lambda\cdot G(x)$ is a constant.

Now consider the case where the total volume of harvest is restricted. Let the allowable harvest be q^*, so q-$q^*>0$ represents harvesting violation. The harvesting violations are, if detected, subject to a penalty consistent of a fine per unit of excessive catch, f. However, fine only has to be paid if the violation is detected and successfully prosecuted. This is a probabilistic event depending on the enforcement effort exerted by the enforcement agency. Let this probability, the probability of having to pay a fine if one violates, be represented by the function

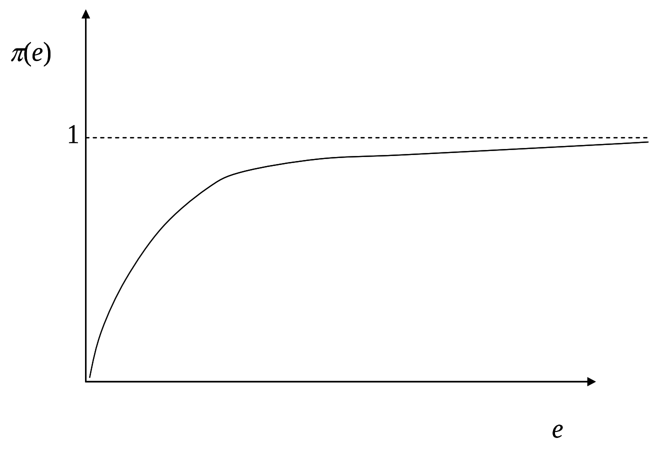
$$\pi(e),$$

which is assumed to be monotonically increasing in enforcement effort, e, and have the property that $\pi(0)=0$ and $\lim_{e\to\infty}\pi(e)=1$.

A possible shape of this function is illustrated in Figure 1.

Clearly, therefore, operating under harvest restrictions and enforcement, the fisher is faced with an additional expected cost defined by:

Figure 1
The penalty probability function



$$\psi(q,e,f,q^*)=\pi(e)\cdot f\cdot(q-q^*),\ \text{if } q\geq q^*,$$

$$\psi(q,e,f,q^*)=0,\ \text{if } q<q^*.$$

So, the expected benefits to a fisher faced with a binding harvest constraint is:

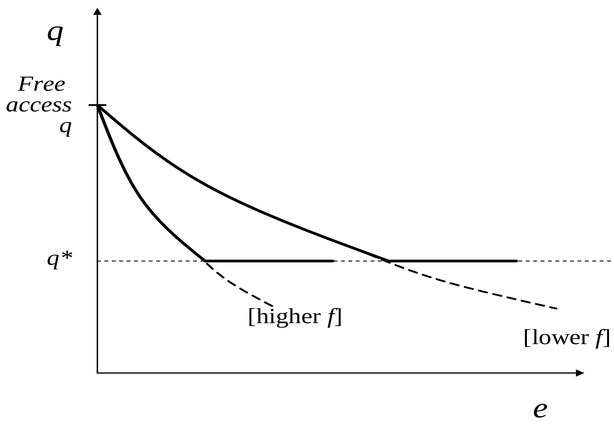
$$B(q,x) - \pi(e) \cdot f \cdot (q - q^*) .$$

Maximizing these benefits with respect to the harvest volume yields the ***enforcement response function****:*

$$q = Q(e, x, f) . \quad (1)$$

This function and its corresponding functions for other restricted fishing activities, is in many respects central to the enforcement situation. It defines the response in the restricted activity to changes in enforcement effort, the level of penalty and other variables. It is easy to show that the enforcement response function is declining in e and f and increasing in biomass, x. The function is illustrated in Figure 2.

Figure 2
The enforcement response function



Enforcement is not free. Presumably, enforcement costs increase in the level of enforcement effort. Let the enforcement cost function be defined by:

$C(e)$,

which is assumed to be at least weakly convex.

The social benefits from fishing under enforcement activity, therefore are:

$$B(q,x) - C(e) - \lambda \cdot q + \lambda \cdot G(x) .$$

2. Optimal enforcement

Given the above, the optimal enforcement problem facing the enforcement agency at each point of time is to adjust the enforcement effort so as to:

$$\underset{e}{Max}\ B(q,x) - C(e)\ - \lambda \cdot q + \lambda \cdot G(x)$$

$$\text{Subject to:} \quad q = Q(e,f,x)$$

Assuming sufficient smoothness and an interior solution, the solution to this problem is:

$$(B_q(Q(e, f, x), x) - \lambda) \cdot Q_e(e, f, x) = C_e(e) . \quad (2)$$

Expression (2) is the fundamental rule for optimal enforcement. With knowledge of the (i) private benefit function, (ii) the enforcement response function, (iii) the cost of enforcement function and (iv) the shadow value of biomass, the functional relationships in (2) can be worked out. This gives an expression for optimal enforcement effort as a function of (i) biomass, (ii) the penalty, *f*, and (iii) biomass as well as other exogenous variables not explicitly listed in (2). This, then is the only thing needed for conducting optimal enforcement.

For economic interpretation (2) is more conveniently written as:

$$B_q(q,x)-\lambda=\frac{C_e(e)}{Q_e(e,f,x)}=\frac{\partial C(e)}{\partial q}, \tag{3}$$

where the last term follows from the identity $\frac{\partial C(e)/\partial e}{\partial Q(e,f,x)/\partial e}=\frac{\partial C}{\partial q}$.

So, under optimal enforcement, the marginal private benefits of fishing less the shadow value of biomass should equal the marginal enforcement cost of harvest. Note that if the harvest constraint is binding, the marginal enforcement cost of harvest must be negative — more harvest implies less enforcement effort *ceteris paribus*. Thus, the term on the lhs of (3) should be negative, i.e. $B_q(q,x)-\lambda$ <0. The usual fisheries optimality rule ignoring enforcement, however, is $B_q(q,x)-\lambda$ =0 [4]. Thus, if enforcement of fisheries rules is costly, optimality requires more harvest than which is suggested by the usual fisheries optimality rule. This is readily understandable; recognizing the enforcement costs of reducing harvests, it is no longer as beneficial to reduce harvests as seemed when the cost of enforcement is ignored. It immediately follows that harvest should not be reduced as much.

OPTIMAL ENFORCEMENT OVER TIME

The optimal enforcement rule expressed in equation (2) applies at each point of time. The rule depends *inter alia* on the shadow value of biomass, λ, applying at the time in question. It does not recognize that λ is really endogenous (in the dynamic sense). Neither does it provide an optimal path of enforcement over time. We now turn to the task of remedying this.

The dynamic enforcement problem is to select a path of enforcement effort, $\{e\}$, that maximizes the present value of net benefits from the fishery. Formally:

$$\underset{\{e\}}{Max}\ V=\int_0^\infty B(Q(e,x;f),x)-C(e)\ \cdot e^{-r\cdot t}dt\,. \tag{I}$$

Subject to: $\dot{x}=G(x)-Q(e,x;f)$.

$x(0)$, given

The differential constraint $\dot{x}=G(x)-Q(e,x;f)$ represents the evolution of the biomass over time with $G(x)$ representing the natural biomass growth. The term $e^{-r\cdot t}$ is the discount factor with *r* being the rate of interest and *t* referring to time. The functional *V* is simply the present value of net economic benefits from the fishery. All the other functions and variables have been defined above.

The Hamiltonian appropriate to this problem may be written as:

$$H=B(Q(e,x;f),x)-C(e)+\lambda\cdot(G(x)-Q(e,x;f)), \tag{4}$$

where λ represents the shadow value of biomass.

The necessary conditions for maximizing the present value of social benefits (i.e. solving I) include:

$$(B_q - \lambda)\cdot Q_e = C_e, \text{ all } t. \tag{4.1}$$

$$\dot{\lambda} - r\cdot\lambda = -B_q\cdot Q_x - B_x - \lambda\cdot(G_x - Q_x), \text{ all } t. \tag{4.2}$$

Condition (4.1) simply states that the enforcement effort should maximize the Hamiltonian function at each point of time. This, it is readily seen, is equivalent to the optimal enforcement rule expressed in (2) above where λ was taken to be exogenous. Expression (4.1), therefore, confirms that rule as being dynamically correct.

Condition (4.2) extends previous results by recognizing the endogeneity of λ. It describes how λ should evolve over time to maximize (4) with this evolution depending among other things on the enforcement effort.

Conditions (4.1) and (4.2) with certain additional conditions (the differential constraint and initial and terminal conditions) can be used to derive the optimal path of enforcement over time. That exercise, however, is in general quite complicated. A numerical example will be provided below.

It is informative, however, to consider the optimal equilibrium. In equilibrium $\dot{\lambda} = 0$. Imposing that and solving (4.1) and (4.2) for *e* and *x* yields the, hopefully, familiar-looking equilibrium expression [3],[4].

$$G_x + \frac{C_e\cdot Q_x + B_x\cdot Q_e}{B_q\cdot Q_e - C_e} = r. \tag{5}$$

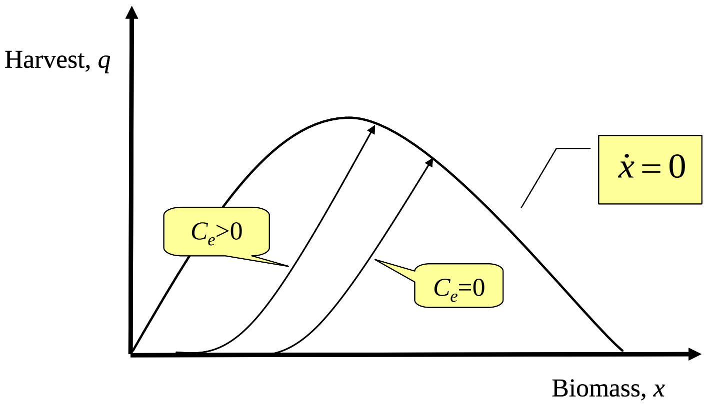
The 2nd term on the l.h.s. of (5) is the so-called marginal stock effect made famous by [3]. Let us refer to this term as Γ.In the traditional fisheries approach, the cost of enforcement is ignored (implicitly assumed to be zero) in which case the marginal stock effect reduces to $\Gamma = \frac{B_x}{B_q}$ and (5) reduces to the usual equilibrium condition [3],[4].

$$G_x + \frac{B_x}{B_q} = r. \tag{5'}$$

Obviously, in both cases, if biomass has no effect on fisheries benefits, Q_x=B_x=0 and Γ=0. Thus, the marginal stock effect, in a sense, reflects the importance of biomass for net benefits. If $\Gamma \neq 0$, its role is to modify the golden rule of capital accumulation, $G_x = r$. In the traditional fisheries model which ignore the costs of enforcement $\Gamma = \frac{B_x}{B_q} > 0$, so the impact of the marginal stock effect is always to encourage a higher stock level than would otherwise be the case. Under costly enforcement, however, $\Gamma = \frac{C_e\cdot Q_x + B_x\cdot Q_e}{B_q\cdot Q_e - C_e}$ which can be of any sign. It follows that under costly enforcement, the optimal equilibrium stock level may be well below the maximum sustainable yield.

Since we have already established (equations (3) and (4.1)) that the optimal harvest at each point of time under costly enforcement is always higher than the optimal harvest when there is no cost of enforcement, it may be conjectured that the two optimal harvesting paths, i.e. under costless and costly enforcement, look similar to those illustrated in Figure 3. It further follows that enforcement effort at each level of biomass would be lower under costly enforcement. This seems economically intuitive. The more expensive the activity, the less it should be used everything else being the same.

Figure 3
Optimal approach paths: conjectures



A NUMERICAL EXAMPLE

Let us now illustrate the above theory with the help of a numerical model. For this purpose we endow the above theory with reasonable functional and parametric specifications. On that basis we calculate approximately optimal fisheries feed-back policies for fisheries enforcement.

The above theory requires us to specify (i) a private fisheries benefit (or profit) function, (ii) a probability of penalty function, (iii) an enforcement cost function and (iv) a biomass growth function.

The private fisheries benefit function is defined as:

$$B(q,x) = p \cdot q - c \cdot \frac{q^2}{x} - FK \ ,$$

where p represents price of harvests, c a variable cost term and FK fixed costs.

The probability of paying the penalty function is specified as:

$$\pi(e) = \frac{e}{\eta + e} \ ,$$

where η is a parameter.

The cost of enforcement is taken to be:

$$C(e)=a \cdot e,$$

where a is a cost parameter.

Finally the biomass dynamics are specified in discrete time as:

$$x_{t+1} = x_t + G(x_t) - q_t \ .$$

$$G(x_t) = \alpha \cdot x_t - \beta \cdot x_t^2 \ ,$$

where α and β are biological parameters.

Consider now the case where fishers' harvest is subject to restrictions and violations, if detected, subject to fines. Then the fishers are faced with the net benefit function:

$$B(q,x) - f \cdot \pi(e) \cdot q = p \cdot q - c \cdot \frac{q^2}{x} - FK - f \cdot \pi(e) \cdot q\,,$$

where f is the fine per unit of violation. Note that for presentational simplicity we have assumed that the allowable harvest is zero, so all catches are strictly illegal. On course, in real enforcement the allowable or target rate of catch would normally be set to a positive value. Moreover, it would probably be variable over time in which case it also becomes a control variable in the optimal control problem. Extending the analysis in this way, however, adds very little of relevance to this paper while complicating the presentation significantly.

Given this specification, the fishers' behavioural function, i.e. their level of harvest is:

$$Q(e,x,f) = \frac{(p - f \cdot \pi(e)) \cdot x}{2 \cdot c}\,.$$

Note that the harvest level is increasing in both the price of fish and biomass, but falling in the level of fine and the probability of having to pay it.

Finally, for the dynamic optimization, we need to specify the rate of discount, r.

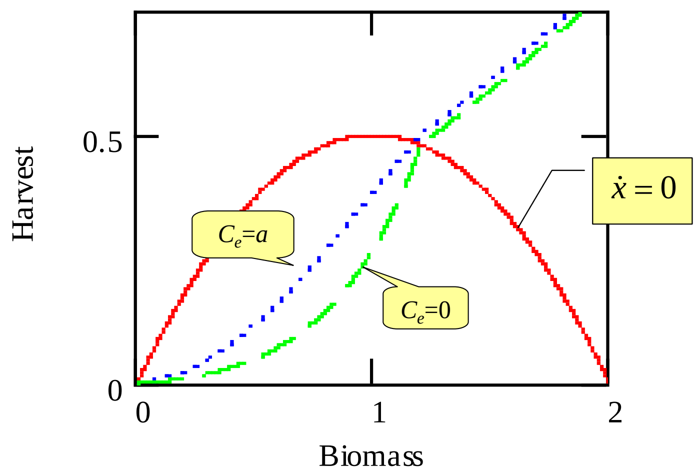
The values of the relevant numerical parameters are given in the following table

α	1
β	0.5
p	1
f	2
a	0.1
η	0.5
c	0.7
FK	0.2
r	0.05

The approximately optimal feed-back paths (for harvest) under costless and costly enforcement are provided in Figure 4. As can be seen from the figure, the optimal harvest for each level of biomass is always greater under costly enforcement than under costless enforcement. Also, under costly enforcement, harvest commences at a lower stock level than when enforcement is costless. Both of these results are in accordance with the theoretical conjecture in the previous section. Numerical calculations further show that as enforcement costs increase the optimal harvest (at each given level of biomass) also increases. At a certain level of enforcement costs, zero enforcement becomes optimal and the optimally managed fishery reverts to the unmanaged one! This, while not generally recognized, is, of course, economically highly intuitive. If the cost of obtaining a certain benefit is too high, it is optimal not to obtain it.

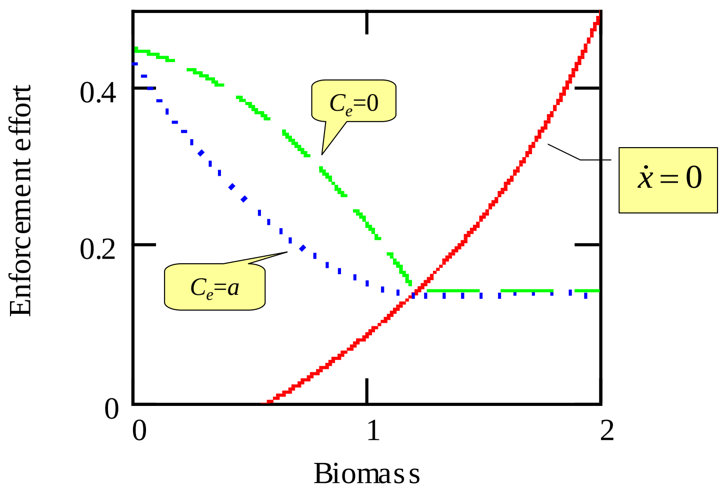
It is perhaps more helpful to view the optimal feed-back paths for enforcement effort (i.e. feed-back in enforcement effort-biomass space). This is illustrated in Figure 5. As expected, optimal enforcement effort is highest for biomass which corresponds to a high shadow value of biomass, and then declines as biomass increases and its shadow value falls. It is curious to note that for biomass levels above the optimal equilibrium level, the optimal enforcement effort stops declining with the biomass, even if the shadow value of biomass is still falling. The reason is likely numerical. We are using a discrete time model here to approximate a continuous time theory. Therefore, for a very high biomass level, the fishery is very profitable and it may simply be the case that too low enforcement will reduce the biomass below the optimal equilibrium level.

Figure 4
Approximately optimal feed-back paths
(Harvest-biomass space)



As before, we see that when enforcement is costly, the level of enforcement is always lower than when enforcement is costless. The difference, however, depends on the level of biomass in a non-monotonic way. For very low biomass levels, the optimal enforcement is high and almost the same irrespective of the whether it is costly or not. The reason seems to be the overriding need to rebuild the stocks fast. As biomass increases the difference also grows for a while and then it declines again. In equilibrium the difference is again relatively small and the same applies for biomass levels above the equilibrium. Why that is the case is unclear. The reason may be that at relatively large volumes of biomass, enforcement effort is low anyway and the cost of enforcement not that significant.

Figure 5
Approximately optimal feed-back paths
(Enforcement effort-biomass space)



DISCUSSION

The optimal dynamic fisheries policy is strongly dependent on the cost of enforcement. The allegedly optimal paths derived by employment of the conventional fisheries models (which ignore enforcement costs) are not truly optimal unless enforcement costs are actually zero. The empirical evidence is that real enforcement costs seem to be quite high relative to fisheries revenues, not to mention fisheries profits [5]. For reasonable enforcement costs, as those employed in the numerical model in section 3 of this paper, the difference between the resulting optimal harvesting paths and those derived on the basis of the conventional fisheries models assuming zero enforcement costs are quite large. One must conclude that fisheries advice on the basis of the conventional fisheries models may be seriously misleading.

The optimal level of enforcement depends on all variables affecting the private benefits of fishing and the cost of enforcement. Among these variables is the biomass level of the fish stocks, price of fish and so on. It immediately follows that the optimal enforcement activity is in general not only variable but likely to exhibit a trend which would be declining as previously depleted fish stocks are rebuilt.

This has obvious implications for the design and structure of the fisheries enforcement agencies which in most countries are entrusted with the fisheries enforcement function. They should in general not be designed for a constant enforcement activity level. Most likely they should be designed to have a declining enforcement activity over time, especially if they are expected to do a good job to start with. Only in biomass equilibrium should, the fisheries enforcement activity stay at a fairly constant level over time.

High enforcement costs reflect the combination of enforcement costs per unit of enforcement and the productivity of the enforcement effort in generating compliance. That in turn depends on the multiple of the penalty and the effectiveness of the enforcement effort in generating likelihood of having to pay the penalty.

Obviously, high enforcement costs can easily render fisheries management uneconomical. This will apply particularly in situations where the basic fisheries management system is of low quality. In those cases, which may well apply in many actual fisheries, attempts at improving fisheries management by research and strengthening fisheries enforcement by additional funds, will most likely make an already bad situation worse. In certain case, enforcement costs may be so high that fisheries management is not worth while, even when the perfect fisheries management system is available.

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