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Swedish COBECOS Pilot Study D2. Estimation

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Swedish COBECOS Pilot Study D2. Estimation

Deliverable 2

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Delivery D2. Estimation

Swedish COBECOS Pilot Study

Preface

According to the Swedish COBECOS pilot study contractual obligations, a report of assessment of estimations should be made available as a deliverable (D2) in month 12. The following report constitutes the fulfilment of this obligation.

The report is conducted in three parts:

1) Assessment of estimates of theoretical enforcement relationships.
2) Method for estimating the shadow value
3) Extension of the theory to include administrative and newer control tools.

In addition to the contractual obligations SwAM is also delivering two R- models of the two fisheries.

Gothenburg 18 March 2013

1. CONTENT

PART 1 Assessment of estimates of theoretical enforcement relationships.

1. Background

Fisheries
The fisheries have been defined based on the gear types included in the management plans for cod (Council Regulation (EC) No 1098/2007 and (EC) 1342/2008).

Table 1. Gear definitions

Gear code	Gear name	Gear identification (>= 90 mm)	COBECOS 1 W (ICES IIIa, IV)	COBECOS 1 E (ICES IIIbcd)
SDN	Danish seiners	221	1	1
OTB	Otter trawl bottom	300	1	
OTB	Otter trawl bottom	309	1	
OTB	Otter trawl bottom	310	1	
OTB	Otter trawl bottom	312	1	1
OTB	Otter trawl bottom	319	1	1
PTB	Pair trawl bottom	320	1	1
OTB	Otter trawl bottom	330	1	1
OTB	Otter trawl bottom	331	1	
OTB	Otter trawl bottom	332	1	
OTB	Otter trawl bottom	333	1	
PTB	Pair trawl bottom	334	1	
OTM	Otter trawl midwater	323		1
OTM	Otter trawl midwater	324	1	1

Enforcement tools
Data on landings and administrative controls are provided. At the planning stage of the project the model was foreseen to also include data on sea going controls. However, during the data collection it became apparent that there were a very limited number of infringements at sea for the vessels of the two COBECOS fisheries in the last three years. Hence, sea-going control could not be included in the COBECOS model.

The data regarding landings controls concern Swedish fishing vessels landing in Swedish ports. A large part of the Swedish fleet is in fact landing abroad, in Denmark etc. However, there is currently not sufficient information for vessels landing abroad and fishing trips with landings in other countries than Sweden has been excluded.

A landing control is defined as the period between when the inspectors leave and return to the control station. Hence, costs for travelling as well as for the actual control are included.

Administrative controls are defined as all verification in logbooks regarding quantity and geographical position. Administrative controls have been carried out for all fishing trips disregarding the place of landing.

Infringement types

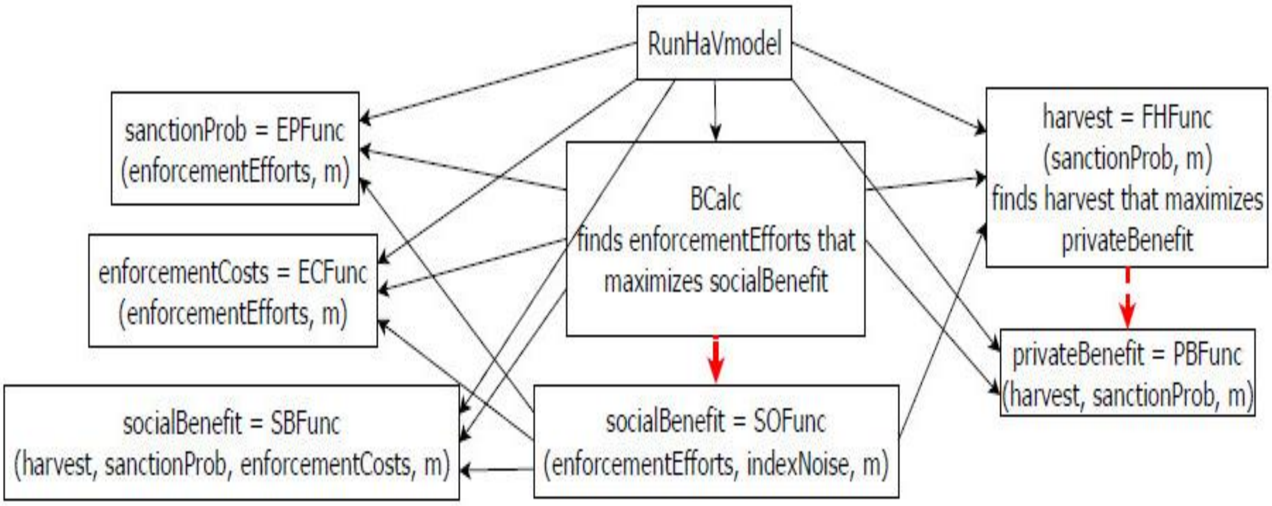
The vessels of the two COBECOS fisheries operate under more than 20 fisheries rules. In order to ensure more observations per infringement type and to avoid having to estimate a vast number of probability functions the infringements have been group into four categories:

1. Logbook errors
2. Prenotification failures or delays
3. Other administrative sanctions
4. Court cases

Since the COBECOS theory is built around detected infringements, the number of detected infringements is crucial for the outcome of the model. For the two Swedish fisheries chosen for analysis the number of detected infringements within the period was limited.

2. The model

In the estimation work SwAM decided to go further than indicated in the contract and develop a model in R of the two Swedish fisheries. The model is constructed according to the below illustration:



The script of the model is delivered in a separate document accompanying this report.

Considering that the COBECOS model was developed as a tool for managers and enforcement officers the aim of the Swedish modelling efforts was to build a model as simple and user-friendly as possible.

3. Estimation

In order to calculate the social benefits of the landings and administrative control activities the following five functional forms or estimates has been calculated:

- The probability of penalty function
- The enforcement cost function
- The penalty function
- The private benefit function
- The social benefit function

3.1 The probability of penalty function

The probability for the fisher to receive a penalty when violating depends on a number of factors such as the type of management measure and type of enforcement tools. In addition, a number of social factors such as peer pressure and the general compliance level in the country are driving factors of the probability of detection. Due to modelling difficulties of social factors only factors that are given in monetary terms or that can be translated into monetary terms (penalties, withdrawal of license etc.) are included as drivers of compliance in the COBECOS model.

In the COBECOS model, the probability of penalty function is defined as the probability of receiving a sanction if violating a management measure.

$$\pi(e) = p(\mathrm{S} \mid \mathrm{V})$$

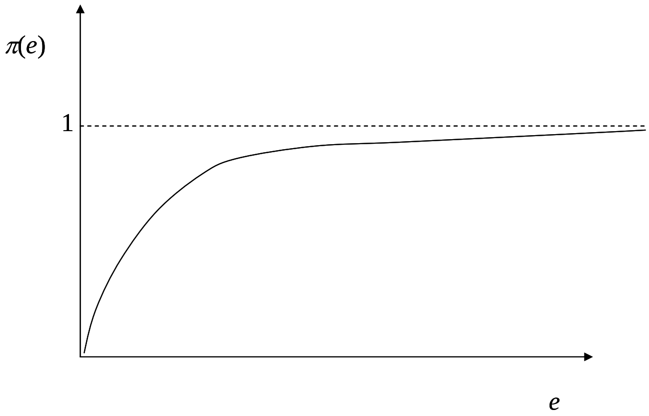
A fair assumption is made stating that all detected infringements are sanctioned. That is:

$$\pi(e) = p(\mathrm{S} \mid \mathrm{V} \cap \mathrm{C}) = 1$$

The probability of penalty is assumed to increase with the intensity of employed enforcement effort (e), i.e. number of controls in a given year.

Figure 1

The penalty probablity function



In a scenario where all fishing activity is controlled it is thought that all or close to all infringements of the particular management tool will be detected. Hence,

$$\mathrm{Max}(e) = 1$$

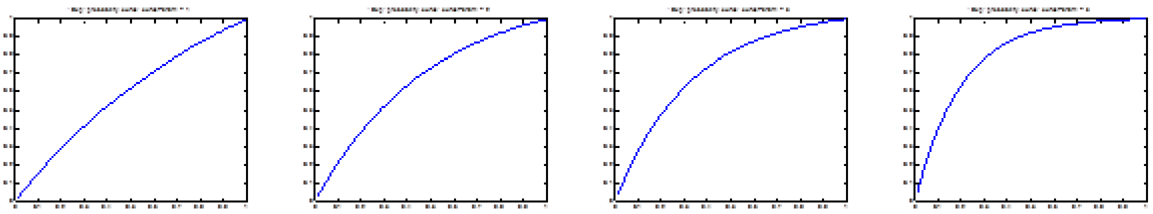
There were very few detected and sanctioned infringements in the two fisheries (see table 2 below). Hence, there were not enough observations to estimate the relationship between enforcement effort and the probability of detection.

Table 2. Number of sanctions

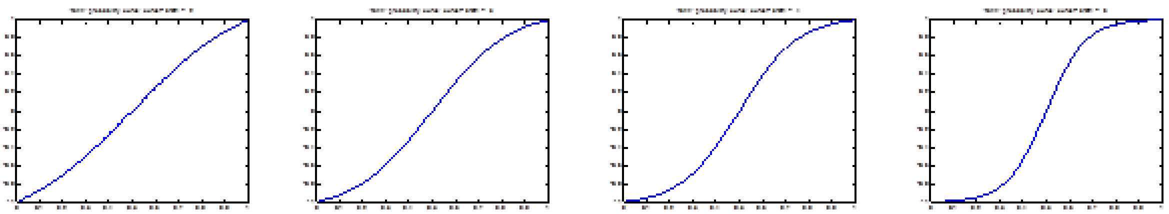
	2009		**2010**			**2011**	
Fisheries	Admin.	Landings	Admin.	At sea	Landings	Admin.	Landings
Cobecos 1 W	27	5	8	1	8	13	1
Cobecos 2 E	10	2	-	-	3	3	5

To construct the model a set of different theoretical functional forms was tested. These are illustrated below.

Example ‘Exponential’ curves with different parameter values, 1.0, 2.0, $\boxed{3.0}$, 5.0:
p = (1.0 - exp(-curveParam*e)) / (1 - exp(-curveParam))



Example ‘tanh’ curves with different parameter values 2, 3, $\boxed{4,}$ 6:
p = tanh(curveParam * (e - 0.5)) / tanh(curveParam * 0.5)



The parameter values indicated with a box are used in the model.

3.2. The enforcement cost function

The two enforcement types included in the model generate two different cost functions:

C_l= cost per landings control

C_2= cost per administrative control

3.2.1 Landings control

The cost per control is defined as all costs associated with preparation, travelling to the control location, inspection and legal costs in the case infringements were detected. The data collection was exhaustive and the cost per landings control can be described as below:

Cost per control $(c_l) = c_{inspector}(t_{preparation}+t_{admin}+2t_{inspection}+2t_{travel})+2(c_{travel}*c_{inspector})+c_{legal}+c_{variable}$

$c_{inspector}$ = Wage per hour (including social costs).

$t_{preparation}$= Preparation time per inspection.

t_{admin}= Time for administration per inspection

$t_{inspection}$= Time per inspection

t_{travel} = travel time from control office to the inspection site.

c_{travel} = travelling cost (cost of cars and fuel)

c_{legal}= legal cost per control (calculated from the legal cost per infringement)

$c_{variable}$ = variable costs

The cost per control is inserted as a cost parameter in the model.

3.2.2 Administrative control

The cost per control is associated with all costs verifying catch quantity and geographical position.

Cost per administrative control $(C_2) = c_{inspector}*(t_{inspection} + t_{admin} + t_{preparation}) + c_{legal}*t_{infringement}$

$c_{inspector}$ = wage per hour (including social costs).

$t_{preparation}$= preparation time per inspection.

t_{admin}= time for administration per inspection

$t_{inspection}$= time per inspection

c_{lega}l= legal cost per inspection (calculated from the legal cost per infringement)

$t_{infringement}$ = *time for legal expert per inspection (calculated from the legal time per infringement)*

3.3 Penalty function

According to the COBECOS theory a penalty function that illustrates how the penalty changes with the level of infringement should be estimated. Sweden has two legal systems for fisheries offences, criminal and administrative sanctions. There were too few criminal sanctions to include these in the model for the two fisheries Therefore, only administrative sanctions are included. The level of theses sanctions are fixed in accordance with national legislation and not dependent on the level of infringements. For this reason a penalty parameter was used in the model.

3.4 Private benefit function

In the COBECOS theory it is assumed that the fisher will fish up to the point, legally or illegally, that maximises the private benefit. The private benefit function can take various forms. SwAM has for the sake of simplicity, chosen to use the function given in the COBECOS theory:

$$PB(f,x) = p*q - c_f*c_{adj} *\frac{q^2}{x}$$

p= price

q= catch

c_f =fishing cost

c_{adj} = cost adjustment factor

x = the biomass

The derivative shows that there is a marginal stock effect, ie that CPUE increased with the size of the biomass.

3.4. Shadow value

Based on the data available the shadow value could not be assessed. For modelling purposes a “guesstimate” was used.

3.5. Social benefits

The following model was used to calculate the Social benefit function.

$$SB = (p-\lambda) *q - c_{adj} * c_f * \frac{q^2 - c_e}{x}$$

P= price
λ = shadow value of biomass
q = catch
c_{adj} = cost adjustment factor
c_f = fishing costs
c_e = control cost

Concluding remarks

The number of infringements coupled with the very low penalty level for the infringements carried out prevented SwAM to run the COBECOS model successfully with empirical data. In order to make it run some adjustment factors had to be included. These are given in detail in the script of the R model.

Efforts have been made to design a simulation tool. With the anticipation of being used as inspiration for future work, an illustration of the tool is included in the delivery.

PART 2 Assessment of estimates of theoretical enforcement relationships.

On January 13, 2012, I contracted with the Swedish Agency for Marine and Water Management (SwAM) to assist in a pilot study for applying the COBECOS fisheries enforcement methodology. This report constitutes a partial fulfilment of my obligations under this contract, namely item 3.c of the contract.

Reykjavik 29. April 2012

Ragnar Arnason

1. Cobecos enforcement theory: A brief review

The following summarizes the essentials of the fisheries enforcement theory as outlined in the Cobecos project (COBECOS 2009). The term "essentials" is used because the presentation ignores the numerous details of any actual enforcement situation. It should be noted that this theory is not limited to fisheries but covers essentially any centralized enforcement situation.

Faced with a binding harvest constraint, q^*, a fisher is assumed to have the following expected benefit function:

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

where the variables q, x and e refer to the volume of harvest, the size of the biomass and enforcement effort, respectively. The function $B(q, x)$ measures the private benefits (profits and/or utility) the fisher gains from fishing. This naturally depends both on the level of harvest, q, and (positively) on the level of biomass, x. The second term in (1) represents his expected costs of violating the harvest constraint. The difference (q-q^*), which is nonnegative since the constraint is supposed to be binding (the other case is not of interest) is the level of infraction. The parameter f is the penalty for a unit of infraction and the function $\pi(e)$ measures the probability of having to pay that penalty. This of course is monotonically increasing in the enforcement effort, e. [1]

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

(2) $$q=Q(e,x,f,q^*).$$

Since (2) assumes fishers have maximized their benefits (implies the function $B(q,x)$ is concave), the first derivatives of the enforcement response function, Q_e and Q_f are negative. If also B_{qx} is positive, which seems very likely, then Q_x is positive.

[1] The probability and penalty functions in (1) may of course be made more general. E.g. the separable expression $f\cdot(q-q^*)$ could more generally be written as the increasing function $f(q-q^*)$.

The enforcement problem is to select the path of enforcement effort, $\{e\}$, over time such that the present value of private benefits less enforcement costs are maximized subject to the relevant constraints of the problem. Formally:

$$\text{(I)} \qquad \underset{\{e\}}{Max} \int_0^T \left(B(q,x) - C(e)\right) \cdot e^{-r \cdot t} dt$$

Subject to: $q = Q(e, f, x, q^*)$,

$$\dot{x} = G(x) - q,$$

where $G(x)$ is the natural biomass growth function and $C(e)$ is the enforcement cost function. The term $e^{-r \cdot t}$ is the discount factor with r being the rate of discount. The upper limit of the integral, T, is the terminal time which may be infinite. Obviously this problem includes as a sub-problem the selection of enforcement effort at the current time. In what follows, (I) will be referred to as the *Basic enforcement problem*.

The enforcement problem (I) may (but does not have to) be restated in the very convenient form:

$$\text{(II)} \qquad \underset{e}{Max}\ B(Q(e, f, x, q^*), x) - C(e) + \lambda \cdot (G(x) - Q(e, f, x, q^*)),$$

where λ is the shadow value of biomass. It is worth noting that the rule expressed in (II) is really the Maximum Principle of dynamic maximization theory made famous by Pontryagin and his collaborators (1962). Note also that (II) is merely a particular restatement of the *Basic Enforcement Problem.*

In the COBECOS theory, the shadow value of biomass, λ, and biomass, x, were taken to be exogenous data and suggested that current enforcement effort be adjusted to maximize (II). Assuming sufficient smoothness and an interior solution, the solution to this problem is expressed by:

(4) $(B_q(Q(e, f, x, q^*), x) - \lambda) \cdot Q_e(e, f, x, q^*) = C_e(e)$.

So, according to this, to be able to carry out optimal enforcement, the enforcement agency has to know the following[2]:

1. The fishers' private benefit function, $B(q,x)$.
2. The probability of penalty function, $\pi(e)$.
3. The cost of enforcement function, $C(e)$
4. The level of biomass, x
5. The penalty parameter, f
6. The shadow value of biomass, λ

This paper is concerned with how to obtain numerical estimates of λ assuming knowledge of the other items of knowledge.

1.1 It is not strictly necessary to know λ

Since this paper is concerned with finding practical ways to estimate λ, it should be mentioned that it is not strictly necessary to include λ in the enforcement problem. λ is included in the restatement of the Basic enforcement problem in (II) merely because it is convenient, which is the same reason it is included in maximization problems in general. It is possible to restate the Basic enforcement problem in forms that do not involve λ. One such variant is the calculus of variations version of the basic enforcement problem (I)

(IIb) $Max\ B(Q(E(x, \dot{x}, f), f, x), x) - C(E(x, \dot{x}, f)$,

where the role of enforcement effort, e, is played by the expression $E(x, \dot{x}, f)$ derived from the dynamic constraint $\dot{x} = G(x) - Q(e, f, x)$.[3] Solving (IIb) yields an optimal path for x and, therefore, also $\dot{x}$. Given this, the optimal enforcement at each point of time can be obtained from $\dot{x} = G(x) - Q(e, f, x)$.

[2] Note that the fishers' enforcement response function, $Q(e, x, f)$, can be derived on the basis of 1, 2 and 4.

[3] There are certain technical difficulties with the expression $E(x, \dot{x}, f)$. For instance, it does not strictly exist as a function over the whole range of positive x.

While (IIb) avoids the explicit use of λ, this is at the cost of a much more complicated expression and a certain reduction in transparency. It should be noted that λ has not really disappeared from the problem. In (IIb) its role is simply played by other expressions. Thus, the problem of estimating λ in (II) is simply replaced by the problem of obtaining and working with more complicated expressions in (IIb).

2. The shadow value of biomass

In this section, the theory of shadow prices is briefly discussed. This is useful for understanding the proposed method to estimate these prices in section 3 below.

2.1 The general theory of shadow values

The basic enforcement problem is but a special case of the general optimal-control problem (see e.g. Kamien and Schwartz 1981)

(III) $$\underset{\{u(t)\}}{Maximize}\ J = \int_0^T I(x(t),u(t),t)\,dt + F(x(T),T)$$

$$þ.a. \quad \dot{x} = f(x(t),u(t),t),$$
$$x(0) = x_0,$$
$$u(t) \in U, \text{ all } t.$$

In this formulation the function $I(x(t),u(t),t)$ is the objective function, the function $F(x(T),T)$ the terminal function and the function $f(x(t),u(t),t)$ the function of motion. The control variables are denoted $u(t)$ and $x(t)$ represents the state variables. U denotes the set from which the control variables may be selected.

Now assume problem (III) has been solved. That yields a certain value of the functional J which depends on all the data of the problem. Write this as:

$$J^*(x(0);T,r,U).$$

Given this maximum value, the shadow value of the state variables measures the marginal benefits of an increase in the initial level of the respective state variables, $x(0)$ (see e.g. Kamien and Schwartz 1981). Thus, the shadow value of state variable i is defined as:

$$(5) \qquad \lambda^*(i) = \frac{\partial J^*(x(0);T,r,U)}{\partial x(0;i)}.$$

It is well-know that these mathematical shadow values correspond exactly to perfect market prices (see e.g. Dorfman 1969, Kamien and Schwartz 1981, Dixit 1990).

The existence of shadow prices does not depend on the optimal solution to the problem (III). Let $u(x,t)$ represent any rule for the control variable u. Given this feed-back rule, and other particulars of the problem, a certain value for the functional J is defined. Write this as the constrained value function:

$$J(x(0);T,r,U).$$

Then the shadow value of state variable i given this particular control rule is defined exactly as in (5)

$$(6) \qquad \lambda(i) = \frac{\partial J(x(0);T,r,U)}{\partial x(0;i)}.$$

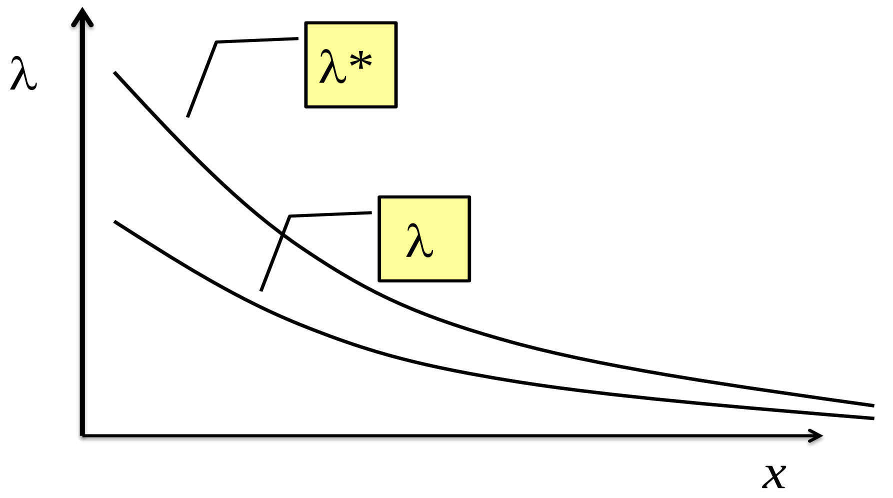
This shadow value, however, will generally be different from the one corresponding to the optimal policy and defined in (5). For the same level of initial biomass, it will normally be lower. The

reason is that normally the optimal policy will make better use of additional biomass. This, however, does not have to be the case in general.

It is useful to note that if x is beneficial the value function J will be an increasing function of $x(0)$. In those cases, λ will be positive. Moreover, J will often be a concave function of $x(0)$. This applies for instance if there are diminishing marginal returns (to utility or production) which is a common rule in economics. In those cases, λ will be a declining function of $x(0)$. Figure 1 illustrates the shape of the shadow values of a beneficial state variable x for the optimal and constrained case under these assumptions.

Figure 1

Typical shapes of shadow values: Unconstrained (λ*) and constrained (λ)



2.2 Fisheries: Shadow value of biomass

For fisheries the above theory of shadow values carries through in a straight-forward manner. Consider for instance the fisheries problem

(IV) $$\underset{\{q\}}{Max}\ V = \int_0^\infty B(q,x)\cdot e^{-r\cdot t}dt$$

Subject to: $\dot{x} = G(x) - q$,

$x(0)$ given

Assume some rule for the level of fishing, i.e. a fisheries feed-back rule. Write this rule as:

(7) $q=Q(x;r)$.

This rule is perfectly general. It depends on all the data of the problem and can take any form as long as it is a function. It may be the solution to the dynamic maximization problem or some other rule. It may be regarded as simply any fishing policy or harvesting rule.

Substituting the feed-back rule into the differential equation and solving it yields the biomass path $\{x\}$ as a function of the initial biomass $x(0)$. Substituting that path into the integral yields the value function $V(x(0);r)$. On that basis the shadow value of biomass can be calculated as:

(8) $$\lambda = \frac{\partial V(x(0);r)}{\partial x(0)}.$$

This shadow value will in general have the same shape as illustrated in Figure 1.

It is important to note the following:

1. The shadow value depends on not only on biomass, which is endogenous to the fishery, but all the other parameters of the problem. These include:
   a. the rate of discount, *r*,
   b. prices which are not explicitly represented in (7)
   c. the fisheries feed-back rule, *Q*(*x*;*r*) which is also not explicit in (7) and
   d. the fisheries management system not explicit in (7)
2. If the value function is low, for instance because of an inefficient fisheries management system, shadow of biomass will be low.

To calculate the value of (8), it is obviously necessary to:

1. Obtain the feed-back rule *Q*(*x;r*) (This may involve solving the maximization problem).
2. Calculate the integral *V* to obtain the maximum value function *V*(*x*(0);*r*)
3. Perform the differentiation in (7). This may of course be approximated by $\lambda = \frac{\partial V(x(0);r)}{\partial x} \approx \frac{V(x(0)+\varepsilon;r) - V(x(0);r)}{\varepsilon}$, where ε is some small addition to the biomass.

2.3 The shadow value under fisheries enforcement

Fisheries enforcement theory shows that the shadow value of the biomass depends not primarily on the fishing policy (harvesting rule) but the level of enforcement (COBECOS 2009). In other words, a more appropriate formulation of the fisheries problem than (IV) is problem (I) as stated in the review of the COBECOS theory in section 1.

(I) $$\underset{\{e\}}{Max} \int_0^T \left(B(q,x) - C(e)\right) \cdot e^{-r \cdot t} dt$$

Subject to: $q = Q(e,f,x,q^*)$,

$\dot{x} = G(x) - q$,

$x(0)$ given

So in this, more realistic fisheries management, the proper control variable is fisheries enforcement rather than the level of harvesting.

The same general principles carry through. Any policy for enforcement can be written as the enforcement feed-back rule:

(9) $e = E(x;r,f,q^*)$.

Note that the only endogenous variable in this formulation is the biomass level, x. All the other arguments in (9) are parameters, i.e. exogenous constants.

Substituting (9) into problem (I) and solving it leads to the value function $V(x(0);r,f,q^*)$. On that basis, the shadow value can be calculated as:

(10) $$\lambda = \frac{\partial V(x(0);r,f,q^*)}{\partial x(0)},$$

And this shadow value can be approximated in the same way as before, namely as:

(11) $$\lambda = \frac{\partial V(x(0);r,f,q^*)}{\partial x(0)} \approx \frac{V(x(0)+\varepsilon;r,f,q^*) - V(x(0);r,f,q^*)}{\varepsilon}$$

To calculate this shadow value, therefore, it is necessary to have an estimate of the value function, $V(x(0);r,f,q^*)$. To obtain that function it is necessary to have the following information.

1. The fishers' private benefit function, $B(q,x)$.
2. The probability of penalty function, $\pi(e)$.
3. The cost of enforcement function, $C(e)$
4. The enforcement response function, $q = Q(e,f,x,q^*)$. This may be derived from the other data.
5. The enforcement feed-back rule, $e = E(x;r,f,q^*)$
6. The current level of biomass, x
7. The penalty parameter, f
8. The rate of discount, r
9. The various prices entering the cost and benefit functions and therefore also the enforcement response function and possibly the enforcement feed-back rule.

2.4 A note on the endogeneity of λ

The shadow value of biomass, λ, is fundamentally endogenous in the enforcement problem as well as other control problems. In the COBECOS theory (see section 1 and, in particular rule (II)), the optimal enforcement effort at each point of time depends on the number used for the shadow value of biomass. The enforcement picked, leads to a specific value function which as described in (8) and (10) defines the shadow value of biomass.

Thus, ideally, the optimal effort level and the shadow value of biomass should be determined simultaneously. Indeed this is the procedure in theoretical optimization theory (Kamien and Schwartz 1981, Dixit 1990).

3. Theoretically consistent optimal enforcement

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:

$$\text{(V)} \qquad \underset{\{e\}}{Max}\ V = \int_0^\infty \left[B(Q(e,x;f,q^*),x) - C(e)\right]\cdot e^{-r\cdot t}dt \,.$$

$$\text{Subject to:} \quad \dot{x} = G(x) - Q(e,x;f,q^*),$$

$$x(0), \text{ given.}$$

Where all the functions and variables have been defined above.

The Hamiltonian appropriate to this problem may be written as:

(11) $H = B(Q(e, x; f, q^*), x) - C(e) + \lambda \cdot (G(x) - Q(e, x; f, q^*))$,

where λ represents the shadow value of biomass.

Necessary conditions for solving this problem include (Pontryagin et al. 1962, Kamien and Schwartz 1981):

(11.1) *e* should maximize *H*, all *t*. (Pontryagin's maximum principle) ⇒

$(B_q - \lambda) \cdot Q_e = C_e$, all t

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

(11.3) $\dot{x} = G(x) - Q(e, x; f, q^*)$, all t

(11.4) $x(0)$= the $x(0)$ that is given.

(11.5) An appropriate transversality condition.

Solving (11.1)-(11.5) together yields the optimal paths of enforcement, biomass and shadow value of biomass over time. While this is theoretically sound, this joint solution is computationally quite demanding and therefore not very practical.

The COBECOS theory attempts to provide a practical approximate solution to the enforcement problem. How does the COBECOS approach compare to the theoretically consistent solution defined by (11.1)-(11.5) above.

- First note that the Hamilton function (11) is identical to the function in the Basic Enforcement Problem in (II) above.

- Second, note that the Basic Enforcement Problem as stated in (II) is exactly Pontryagin's maximum principle (Pontryagin et al. 1962). Indeed the necessary condition (11.1) confirms the COBECOS solution to the enforcement problem as expressed by equation (4). Thus, dynamic optimization theory confirms that rule as being dynamically correct.

- Third, note that under the COBECOS theory necessary conditions (11.3) and (11.4) will be automatically satisfied (facts of life).

- Fourth, the COBECOS theory ignores conditions (11.3) and (11.5), that is the dynamic evolution of the shadow value of biomass. Instead the COBECOS theory takes the current λ simply as a given datum.

Thus, the COBECOS theory deviates from the theoretical ideal by taking λ as given. Note, however, that from a practical perspective this is not much of an error. The reason is that in applying the COBECOS theory, enforcement effort is set at a point of time (or rather for a period such as a year) and not for the whole future. At this point of time, λ, is for the most part given as a function of future expectations for the fishery partly expressed by the enforcement feed-back rule as discussed above. Thus, whatever is done during the first period is not going to alter λ drastically, especially if enforcement effort is set optimally.

4. Theoretically consistent optimal enforcement

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:

$$\text{(V)} \qquad \underset{\{e\}}{Max}\ V = \int_0^{\infty} \left[B(Q(e,x;f,q^*),x) - C(e) \right] \cdot e^{-r \cdot t} dt\,.$$

$$\text{Subject to:} \quad \dot{x} = G(x) - Q(e,x;f,q^*),$$

$$x(0), \text{ given.}$$

Where all the functions and variables have been defined above.

The Hamiltonian appropriate to this problem may be written as:

(11) $H = B(Q(e,x;f,q^*),x) - C(e) + \lambda \cdot (G(x) - Q(e,x;f,q^*))$,

where λ represents the shadow value of biomass.

Necessary conditions for solving this problem include (Pontryagin et al. 1962, Kamien and Schwartz 1981):

(11.1) *e* should maximize *H*, all *t*. (Pontryagin's maximum principle) ⇒

$(B_q - \lambda) \cdot Q_e = C_e$, all *t*

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

(11.3) $\dot{x} = G(x) - Q(e,x;f,q^*)$, all *t*

(11.4) *x*(0) = the *x*(0) that is given.

(11.5) An appropriate transversality condition.

Solving (11.1)-(11.5) together yields the optimal paths of enforcement, biomass and shadow value of biomass over time. While this is theoretically sound, this joint solution is computationally quite demanding and therefore not very practical.

The COBECOS theory attempts to provide a practical approximate solution to the enforcement problem. How does the COBECOS approach compare to the theoretically consistent solution defined by (11.1)-(11.5) above?

- First note that the Hamilton function (11) is identical to the function in the Basic Enforcement Problem in (II) above.

- Second, note that the Basic Enforcement Problem as stated in (II) is exactly Pontryagin's maximum principle (Pontryagin et al. 1962). Indeed the necessary condition (11.1) confirms the COBECOS solution to the enforcement problem as expressed by equation (4). Thus, dynamic optimization theory confirms that rule as being dynamically correct.

- Third, note that under the COBECOS theory necessary conditions (11.3) and (11.4) will be automatically satisfied (facts of life).

- Fourth, the COBECOS theory ignores conditions (11.3) and (11.5), that is the dynamic evolution of the shadow value of biomass. Instead the COBECOS theory takes the current λ simply as a given datum.

Thus, the COBECOS theory deviates from the theoretical ideal by taking λ as given. Note, however, that from a practical perspective this is not much of an error. The reason is that in applying the COBECOS theory, enforcement effort is set at a point of time (or rather for a period such as a year) and not for the whole future. At this point of time, λ, is for the most part given as a function of future expectations for the fishery partly expressed by the enforcement feed-back rule as discussed above. Thus, whatever is done during the first period is not going to alter λ drastically, especially if enforcement effort is set optimally.

5. Practical estimation of the shadow value of biomass

It is not very practical to solve the complete dynamic enforcement problem described in section 3. This is quite demanding even for just one enforcement control and one state variable, i.e. biomass (Sandal et al. 2004). In real fisheries enforcement there are usually several enforcement tools over which enforcement effort can be defined and often several state variables in terms of stocks and stock subsets. This level of complexity renders direct calculation according to the theoretical prescripts virtually infeasible. For this reason, it is of great practical importance to develop a feasible method for selecting a reasonably efficient enforcement effort

The COBECOS theory (expressed by (II) in section 1) is an attempt in this direction. However, to apply this theory it is necessary to obtain estimates of the shadow value of biomass. A practical approximate approach to do this is described below:

Fisheries enforcement effort (over the various enforcement tools) is usually determined for a period of time, often a year. At this point of decision, future fisheries enforcement effort and harvesting in future periods may be taken for granted e.g. as reflected in a presumed enforcement and/or harvesting feed-back rule as discussed in section 2. On this basis and the theory discussed in section 2 and 3 above, the following practical approach to determining the shadow value of biomass consisting of six steps is proposed.

1. Obtain the basic enforcement model

   This is summarized by the expression:

   $$B(Q(e,x;\, f,q^*),x) - C(e) + \lambda \cdot (G(x) - Q(e,x;\, f,q^*)).$$

   And requires knowledge of the items discussed in 2.3

2. Specify the enforcement feed-back rule, $e = E(x;r,f,q^*)$. Alternatively, the harvesting rule $Q(x;r)$ may be used (see 2.2). These rules may be dynamic, i.e. shift over time.

3. Assume future values of the exogenous parameters such as r, f, q^* and prices.

4. Calculate the value function $V(x(0);r,f,q^*)$ for a few strategically selected $x(0)$'s.

5. Fit with the help of regression methods a simple function to these calculated points. This yields an estimated value function as a function of the initial biomass level which may be denoted as:

   $$\hat{V}\left(x(0);r,f,q^*\right)$$

6. For the current initial biomass level, $\overline{x}(0)$, say, calculate the shadow value of biomass.

Clarifications

Step 1. The construction of the basic enforcement model requires knowledge of the items discussed in section 2.3

1. The fishers' private benefit function, $B(q,x)$.
2. The probability of penalty function, $\pi(e)$.
3. The cost of enforcement function, $C(e)$
4. The enforcement response function, $q = Q(e,f,x,q^*)$. This may be derived from the other data.
5. The current level of biomass, $x(0)$.
6. The penalty parameter, f
7. The rate of discount, r
8. The various prices entering the cost and benefit functions

Step 2. The enforcement rule or harvesting rule that should be employed should be the best guess of future policy. As mentioned, these rules may evolve over time or shift at one.

Step 3. This is straight forward prediction.

Step 4. This requires the calculation of the expression:

$$V(x(0),r,f,q^*) = \int_0^\infty \left[B(Q(E(x;r,f,q^*),x;f,q^*),x) - C(E(x;r,f,q^*))\right]\cdot e^{-r\cdot t}dt\,.$$

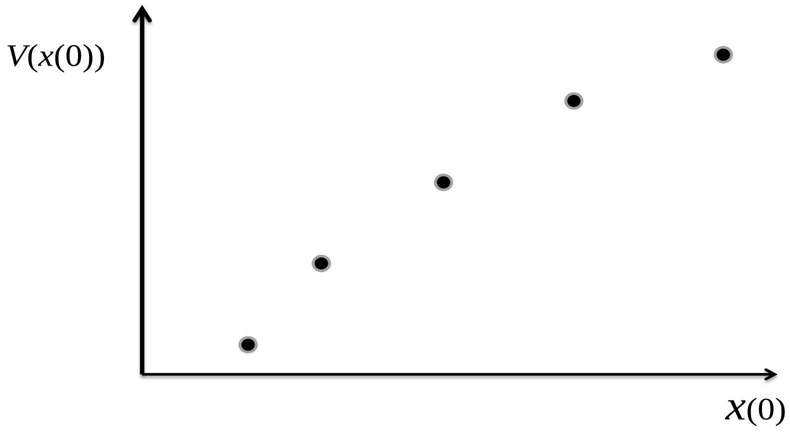
Subject to: $\dot{x} = G(x) - Q(E(x;r,f,q^*),x;f,q^*)$, $x(0)$ given.

which is a considerable task. However, the advantage is that this only needs to be done once for each $x(0)$ selected. Although, of course, if some of the data, such as prices change, it may be deemed worthwhile to redo the calculations. One of the initial biomass points selected should be the optimal equilibrium whose value function is comparatively easy to calculate

For five different initial biomass levels, this exercise will generate a value function scatter diagram as illustrated in Figure 2

Figure 2

Examples of value function levels

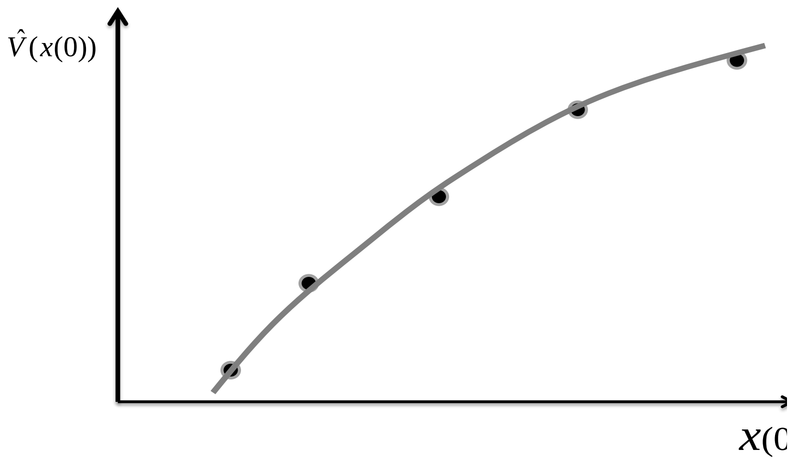


s worth noting that environmental concerns can easily be included in the fishery value function by adding a term such $\Psi(x)$ which is strictly positive and increasing in biomass, x .

Step 5. The fit to the value function data points will usually be satisfactory with a simple functional form such as $\hat{V} = \alpha \cdot \ln(x(0) + \beta)$ or a simple polynomial noting that the value function should be non-decreasing in biomass. The outcome will be as illustrated in Figure 3

Figure 3

A fitted value function



Let us refer to this estimated value function as

$$\hat{V}(x(0);r,f,q^*)$$

Step 6. Given the estimated value function, it is easy to calculate the shadow value of biomass as either the first derivative of the estimated value function:

$$\lambda = \frac{\partial \hat{V}(x(0);r,f,q^*)}{\partial x(0)}$$

Or, if this derivative is not available, the approximation:

$$\lambda = \frac{\hat{V}(\bar{x}(0)+\varepsilon;r,f,q^*)-\hat{V}(\bar{x}(0);r,f,q^*)}{\varepsilon}.$$

There are several important advantages to the approach to estimating the shadow value of biomass described above.

(1) The first and most important advantage is that it is perfectly feasible and, compared to solving the dynamic maximization problem in full, quite trivial.

(2) The second great advantage is that it is theoretically consistent. Thus, if the enforcement feed-back rule is in fact optimal, then this method of determining the shadow value of biomass will lead to enforcement effort that actually replicates the enforcement feed-back rule.[4]

(3) The third advantage is that this process in informationally accumulative. Thus, as an increasing number of value function points are calculated over time with different values of

[4] I believe I can prove this mathematically, but the proof is outside the scope of this study.

the exogenous variables *f*, *q**, *r* and so on, the data basis for estimating a more complete value function including parameters for these varying parameters as well as different biomass levels is generated. Thus, pretty soon, it will be possible to calculate the response of the shadow value of biomass to these parameters as well.

6. Calculations of shadow values: A simple numerical example

What follows is a very simple example of calculation of shadow values on the assumption that data points for the value function have been calculated. It is of course possible to compute a numerical example from the scratch (the basic bioeconomic model), but that is considerably more work.

Let there be four estimates of the value function as follows:

Biomass	Value
50	0,38
100	5,60
250	16,27
1000	40,51

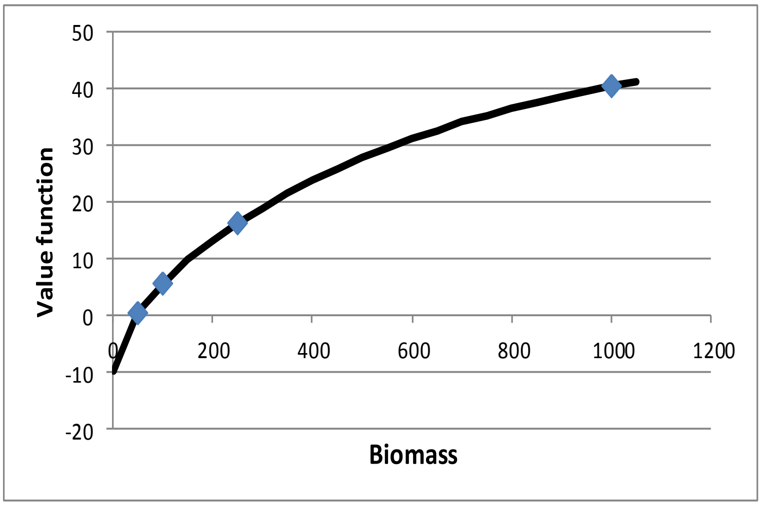
A polynomial equation that fits these points exactly is:

$$\hat{V}(x(0)) = x(0)^{0.6} - 0.0001 \cdot x(0)^{1.7} - 10 .$$

This yields the estimated value function graph:

Figure 3

The estimated value function



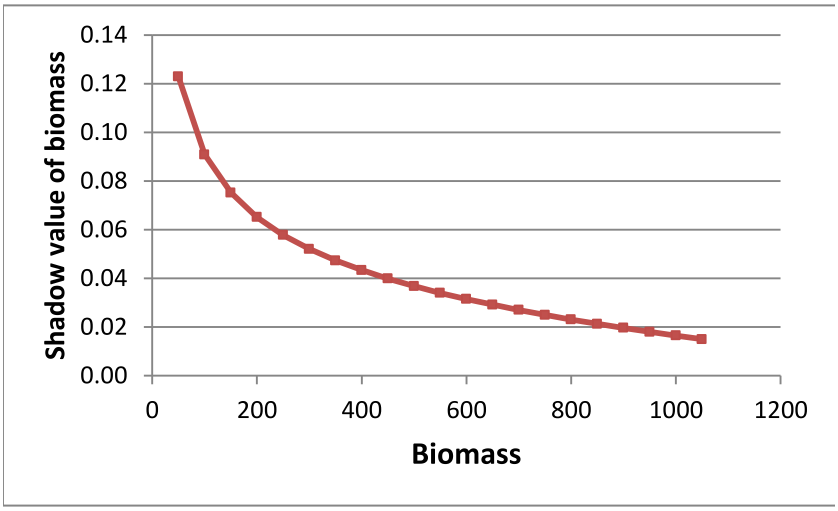
It immediately follows that the shadow value of biomass at different levels of biomass is estimated by the expression (see section 4):

$$\lambda = \frac{\partial \hat{V}(x(0); r, f, q^*)}{\partial x(0)} = 0.6 \cdot x(0)^{-0.4} - 0.00017 \cdot x(0)^{0.7}.$$

So, for any level of initial biomass the shadow value can be easily calculated by simply plugging the biomass into this equation. The graph of the shadow value is illustrated in Figure 4.

Figure 4

The estimated shadow price function



As already mentioned, it is of course possible to derive the value function and the associated shadow values for any specified bio-economic enforcement model, provided the other data mentioned in chapter 4 are also provided. Depending on the complexity of the model, this may be significant work, however. The main reason is that it involves the calculation of an integral over time. The advantage is that only a few value function points have to be calculated.

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PART 3 Extension of the theory to include administrative and newer control tools.

On January 13, 2012, I contracted with the Swedish Agency for Marine and Water Management (SwAM) to assist in a pilot study for applying the COBECOS fisheries enforcement methodology. This report constitutes a partial fulfilment of my obligations under this contract, namely item 3.d of the contract.

Reykjavik 1. May 2012

Ragnar Arnason

1. Introduction

The fundamental COBECOS enforcement theory (COBECOS 2009) is quite general. The basic theory can accommodate a wide range of management controls and enforcement tools. However, to incorporate specific enforcement tools in the basic theoretical structure in a proper way is not always straight forward. This paper attempts to explain further how this can be done. More specifically, it considers certain novel types of enforcement tools; VMS (vessel monitoring system), ERS (electronic recording and reporting system) and ACC (administrative cross checks). Also, due to a special request, it says a few words about the enforcement of discarding rules.

The paper is organized as follows. The general COBECOS theory of multiple management controls and enforcement tools is laid out in section 2. In section 3, the application of this theory to VMS, ERS, ACC is discussed and explained. Section 4 deals specifically with the enforcement of discarding restrictions.

2. Multiple enforcement tools

In this section the basic COBECOS enforcement theory is extended to include (i) multiple fisheries activities — not just the volume of harvest, (ii) multiple management controls (targets) — not just landings and (iii) multiple enforcement tools — not just enforcement of landings. As will become apparent, the basic theory extends in a straight-forward manner in this respect.

2.1 Fishers' actions

Let all possible fishers' actions (including fishing time, search time, crew size, gear type, location etc.) be represented by the vector ***s***.

Harvests are produced by:

$$q = Q(\boldsymbol{s}, x),$$

where x is biomass. It is convenient to refer to the (I+1) vector ($\boldsymbol{s}$,q) supposed to be (1xI) as the vector of possible fisheries actions.

With general fisheries actions, instead of just harvests, there may be some impacts on the biomass growth function. For instance mesh size, timing of fishing and fishing areas may influence the growth of the biomass. A general modelling of this is:

$G(x,\boldsymbol{s})$,

where $G(x,\boldsymbol{s})$ is the biomass growth function, which now depends on the fisheries actions. If some action, s_i, has no effect on the biomass growth function, the corresponding derivative, $G_{s_i}(\boldsymbol{s})$, is identically zero.

Private benefits from fishing before taxes and penalties are defined by:

(1) $B(\boldsymbol{s},x)=p\cdot Q(\boldsymbol{s},x)-C(\boldsymbol{s})$,

where p refers to the price of landings and $C(\boldsymbol{s})$ to the cost of fishers' actions.

2.2 Management controls

Fisheries managers may want to control any or all possible fishers' actions. For instance, they may want to restrict harvests, q, (or landings) or they may want to control fishing time and areas, reduce discards and so on. In general they can impose restrictions on any fishers' actions, i.e. the vector $\boldsymbol{s}$, as well as the harvest, q. We refer to these management restrictions as a management controls.

To be worthwhile fisheries management controls must either alter components of fishers' private benefit functions or the biological constraint. Any other controls are irrelevant to how the fishery is conducted. Clearly, the maximum number of management controls is equal to the dimension of fishers' actions, i.e. I+1 in this case. In practice only a few of these actions will actually be controlled.

It should be noted that fisheries managers may also want to alter the effective landings price or costs by taxation (positive or negative). This is a type of fisheries management and, as other management controls, requires enforcement. This is ignored in the current formulation, but could be included.

2.3 Enforcement tools

Enforcement tools are all the methods enforcement authorities can use to increase adherence to the management controls. There is a great number of possible enforcement tools. Let all possible fisheries enforcement tools (including dock side monitoring, airplane hours, number of on-board observers, number of inspections, VMS, ERS etc.) be represented by an (1xJ) vector. Moreover, let the effort along all these tools be represented by the (1xJ) vector $\boldsymbol{e}$.

There will generally be costs associated with the enforcement actions. Let us express these costs by the enforcement cost function:

$$CE(\boldsymbol{e}).$$

2.3 Penalties

Penalties for violating management controls are given by the vector, $\boldsymbol{f}$. Clearly the dimensionality of this vector equals the number of different management controls. More precisely this vector can be written as:

$\boldsymbol{f}=(f_1, f_2,\ldots.. f_{I+1})$.

If there are no constraints on some possible fishers' action, j, say, the corresponding penalty will be identically zero, $f_j \equiv 0$. Needless to say, in most enforcement situations, most of the elements in the $\boldsymbol{f}$ vector will be zero.

Note that, instead of being parameters as above, the penalties may actually be functions, e.g. of the extent of the violation.

2.4 Probability of penalty

Probability of penalty for violating management restrictions is given by the following vector production function corresponding to all possible fisheries actions and harvests:

$$\boldsymbol{\pi}(\boldsymbol{e}) = (\pi_1(\boldsymbol{e}), \pi_2(\boldsymbol{e}), \ldots \pi_{I+1}(\boldsymbol{e})).$$

Note that in principle all probabilities of penalty depend on all the enforcement efforts. This is because e.g. a landing's observer may detect fishing gear violation and so on. In accordance with the vector of fishers' action in section 2.1, the last item in this vector represent the probability of suffering a penalty for violating harvesting restrictions.

2.5 Private behaviour

Given the above specifications the private (or fishers') maximization problem may be expressed as:

(I) $$\underset{\boldsymbol{s}}{Max}\ B(Q(\boldsymbol{s}, x), x) - \sum_{i=1}^{I} f_i \cdot \pi_i(\boldsymbol{e}) \cdot (s_i - s^*) - f_q \cdot \pi_q(\boldsymbol{e}) \cdot (Q(\boldsymbol{s}, x) - q^*).$$

In this formulation starred, '*', variables refer to the allowable levels of fisheries actions. The simplification that all management controls are represented as an upper bound on the respective fishers' actions is not necessary. A more general formulation is to write this as some function of the action and the management control, $\Gamma(s_i, s_i^*)$, say. For that formulation we may rewrite (I) as :

$$\text{(Ib)} \qquad \underset{\boldsymbol{s}}{Max}\ B(Q(\boldsymbol{s},x),x)-\sum_{i=1}^{I} f_i\cdot\pi_i(\boldsymbol{e})\cdot\Gamma(s_i,s^*)-f_q\cdot\pi_q(\boldsymbol{e})\cdot\Gamma(Q(\boldsymbol{s},x),q^*)$$

The solution to this private maximization problem may be written as the (1x*I*+1) vector function (more generally correspondence):

$$\text{(2)} \qquad \left(\boldsymbol{S}(\boldsymbol{e};\boldsymbol{f},x,\boldsymbol{s}^*,q^*),\quad Q(\boldsymbol{S}(\boldsymbol{e};\boldsymbol{f},x,\boldsymbol{s}^*,q^*),x)\right).$$

Equation (2) is the enforcement response function in the multiple management control, multiple enforcement tool case. It defines how the various fishers' actions depend on the vector of enforcement effort, $\boldsymbol{e}$, biomass, x, and management controls, ($\boldsymbol{s}^*$,q^*).

2.6 Social optimization

The social maximization problem is:

$$\text{(II)}\ \underset{\boldsymbol{e}}{Max}\ B(Q(\boldsymbol{S}(\boldsymbol{e},\boldsymbol{f},x,s^*,q^*),x),x)+\lambda\cdot(G(x,\boldsymbol{S}(\boldsymbol{e},\boldsymbol{f},x,s^*,q^*))-Q(\boldsymbol{S}(\boldsymbol{e},\boldsymbol{f},x,s^*,q^*),x))-CE(\boldsymbol{e})$$

Apart from the generalizations there is one important difference between this social problem and the one in the basic COBECOS theory (COBECOS 2009). This is the inclusion of fishers' action in the biomass growth function. This is because some of the fisher's actions e.g. fishing gear choice, area-time choices and size selectivity may affect biomass growth.

The necessary conditions for solving this problem are informative:

(3) $$\sum_{i=1}^{I}[B_{s_i}+\lambda\cdot(G_{s_i}-Q_{s_i})]\cdot\frac{\partial s_i}{\partial e_j}-CE_{e_j}\leq 0,\quad e_j\geq 0,$$

$$\left(\sum_{i=1}^{I}[B_{s_i}+\lambda\cdot(G_{s_i}-Q_{s_i})]\cdot\frac{\partial s_i}{\partial e_j}-CE_{e_j}\right)\cdot e_j=0,\text{ all } j=1,2\ldots J.$$

Thus, for all management actions which are undertaken ($e_j>0$), the following has to hold

$$\sum_{i=1}^{I}[B_{s_i}+\lambda\cdot(G_{s_i}-Q_{s_i})]\cdot\frac{\partial s_i}{\partial e_j}-CE_{e_j}=0,\quad \text{all } e_j>0.$$

Expression (3) defines the optimal enforcement effort level and therefore also the optimal mix of all possible enforcement tools. The principle is that the enforcement effort for all tools that are used should at a level where it produces the same marginal benefits, namely zero. The level of effort for other tools must equal zero.

Obviously, to work out the solution corresponding to (3) requires knowledge of (i) the private benefit function, (ii) the cost of enforcement function, (iii) the probability of penalty function, (iv) the penalty structure as well as the management restrictions for all possible fishers' actions. With that knowledge in hand, the private maximizing solution in equation (2) can be derived and subsequently the expression for optimal enforcement effort mix given in (3).

3. Specific enforcement tools

In this section we will consider certain specific enforcement tools suggested by SwAM and how they can be modeled within the basic COBECOS fisheries enforcement theory. In all cases we assume that there are two management controls (i) a catch constraint, q^* and (ii) an area constraint, a^*. We also assume that in addition of the specific enforcement tools considered, there are some other tools employed such as dockside monitoring, at-sea monitoring, observer monitoring and so on. In the interest of simplifying the notation, we represent these jointly by one enforcement effort variable, e. For ease of understanding, we will present these examples along the lines set out in the theory in section 2.

3.1 VMS

VMS makes it easier to establish the location of the fishing vessel at all times as well as some other aspects of its behaviour.

***Enforcement model components*:**

Fishers' actions:	Area choice, a; harvest level, q and fisheries inputs, z. Represent this by the vector (a,q,z).
Fishers' benefits:	$B(q,x)$. This assumes that the actions a and z do not affect benefits directly but only through q and x. This is for simplicity of exposition only. More generally the benefit function would be $B(q,x,a,z)$.
Harvest function:	The level of harvest depends on fisheries inputs, area choice and the level of biomass; $q=Q(z,a,x)$
Biomass growth:	$G(x,a)-q$
Management controls:	Area restrictions and catch restrictions, (a^*,q^*).
Enforcement tools:	General enforcement and VMS. The effort on each is represented by the vector (e,e_{VMS}).
Cost of enforcement:	$C(e,e_{VMS})$
Penalties:	Penalties for harvest violations, f_q, and area violations f_a.

Probability of penalty: $\pi_q(e, e_{VMS})$ and $\pi_a(e, e_{VMS})$.

***Private maximization*:**

The problem is:

$$\underset{z,a}{Max}\ B(Q(z,a,x),x) - f_q \cdot \pi_q(e,e_{VMS}) \cdot (Q(z,a,x) - q^*) - f_a \cdot \pi_a(e,e_{VMS}) \cdot (a - a^*)$$

Note that the difference (*a*-*a**) must be interpreted as some measure of area violation.

The necessary conditions are:

$B_Q \cdot Q_z - f_q \cdot \pi_q(e,e_{VMS}) \cdot Q_z = 0$, if z>0,

$B_Q \cdot Q_a - f_q \cdot \pi_q(e,e_{VMS}) \cdot Q_a - f_a \cdot \pi_a(e,e_{VMS}) = 0$, if *a*>0.

Solving these equations produces the enforcement response equations:

$z = Z(e, e_{VMS}, x, f_q, f_a, q^*, a^*)$,

$a = A(e, e_{VMS}, x, f_q, f_a, q^*, a^*)$.

Optimal enforcement

$$\underset{e,e_{VMS}}{Max}\ B(Q(Z(e,e_{VMS},x,f_q,f_a,q^*,a^*),A(e,e_{VMS},x,f_q,f_a,q^*,a^*),x),x)$$
$$+\lambda\cdot(G(x,A(e,e_{VMS},x,f_q,f_a,q^*,a^*),x))-Q(Z(e,e_{VMS},x,f_q,f_a,q^*,a^*),A(e,e_{VMS},x,f_q,f_a,q^*,a^*),x))$$
$$-CE(e,e_{VMS})$$

This maximization problem may seem more complicated than it actually is. Remember that for the maximization only the enforcement efforts e and e_{VMS} are actually variable.

Application: What needs to be done?

The above tell us what needs to be done in addition to the standard COBECOS work. The following functions need to be estimated.

(1) A harvesting function, $Q(z,a,x)$, including area choices needs to be empirically estimated.
(2) The impact of area choice on the biomass growth function, $G(x,a)$, needs to be estimated.
(3) A joint cost function including both enforcement efforts, $C(e,e_{VMS})$, needs to be estimated.
(4) The two joint probability of penalty functions, $\pi_q(e,e_{VMS})$ and $\pi_a(e,e_{VMS})$, need to be estimated.

The parameters, a^* and f_a need to be established just as q^* and f_q.

Apart from this, the application of the theory proceeds in the usual way. Maximization procedures will be more complicated than in the single enforcement effort case but eminently feasible.

3.2 ERS

ERS can contribute to the enforcement of many fisheries management controls. In our example it can contribute to both catch and area restrictions in the same qualitative way as the VMS discussed above. It follows that to apply the COBECOS enforcement theory will proceed in exactly the same way as that described for the VMS above. All that needs to be done is to replace the acronym VMS with ERS

Note that the harvesting function, $Q(z,a,x)$ and the biomass growth function, $G(x,a)$, which only depend on fishers' actions and not on the enforcement tools, do not need to be re-estimated. The probability of penalty functions, $\pi_q(e, e_{ERS})$ and $\pi_a(e, e_{ERS})$ will be different and may well be more difficult to assess.

3.3 ACC

ACC (administrative cross checks) consist of comparing reports from various stages of the harvesting (including log-books), landings, processing, distributional and marketing process in order to detect deviations indicative of violations. This process can contribute to the enforcement of actual catches and several other fishers' actions that are subject to controls. Thus, from an analytical and empirical perspective ACC works in a similar way to ERS or VMS. However, for the sake of illustration let us consider the case where there is only one management control, the volume of harvest, q, and ACC contributes to the enforcement of this.

***Enforcement model components*:**

Fisheries actions:	Area choice, a; harvest level, q and fisheries inputs, z. Represent this by the vector (a,q,z).
Harvest function:	The level of harvest depends on fisheries inputs, area choice and the level of biomass; $q=Q(z,a,x)$
Biomass growth:	$G(x,a)-q$

Management controls: In this case only catch restrictions, q^*.

Enforcement tools: General enforcement and ACC. The effort on each is represented by the vector (e, e_{ACC}).

Cost of enforcement: $C(e, e_{ACC})$

Penalties: Penalties for harvest violations, f_q.

Probability of penalty: $\pi_q(e, e_{ACC})$.

***Private maximization*:**

The problem is:

$$\underset{z,a}{Max}\ B(Q(z,a,x),x) - f_q \cdot \pi_q(e,e_{ACC}) \cdot (Q(z,a,x) - q^*)$$

The necessary conditions are:

$$B_Q \cdot Q_z - f_q \cdot \pi_q(e,e_{ACC}) \cdot Q_z = 0,\ \text{if } z>0,$$
$$B_Q \cdot Q_a - f_q \cdot \pi_q(e,e_{ACC}) \cdot Q_a = 0,\ \text{if } a>0.$$

Solving these equations produces the enforcement response equations:

$$z = Z(e, e_{ACC}, x, f_q, q^*),$$
$$a = A(e, e_{ACC}, x, f_q, q^*).$$

Optimal enforcement

$$\begin{aligned}&\underset{e,e_{ACC}}{Max}\; B(Q(Z(e,e_{ACC},x,f_q,q^*),A(e,e_{ACC},x,f_q,q^*),x),x)\\&\quad+\lambda\cdot(G(x,A(e,e_{ACC},x,f_q,q^*),x))-Q(Z(e,e_{ACC},x,f_q,q^*),A(e,e_{ACC},x,f_q,q^*,x),x)\\&\quad-CE(e,e_{ACC})\end{aligned}$$

4. Enforcing discarding restrictions.

Fisheries management often aims at reducing or eliminating discards. To do so obviously requires enforcement.

The rationale for reducing discards is not always very clear (Arnason 1994). Discarding obviously benefits the fishers; otherwise it wouldn´t occur. This may be detrimental to society for several reasons. First, discarding may distort catch statistics, which often only count landings: Second, discarding of catches may be distressing to a part of the population. Third, discarding may be caused by other restrictions such as individual catch quotas and therefore be socially inefficient while privately beneficial.

The following describes the essential steps in constructing a discarding (and landings) enforcement model.

***Enforcement model components*:**

Fishers' actions: Harvest level, q and discarding, d. Represent this by the vector (q,d).

Fishers' benefits: Discarding in general affects fishers' benefit function. First it must be subtracted from catches which generally reduces benefits. However, if the cost of bringing the discarded catch to shore exceeds the price, discarding is directly beneficial. This would be the case if it happens under no particular

fisheries management (Arnason, 1994). Therefore, in general, the benefit function should be written as $B(q,d,x)$.

Harvest function: Since in this formulation harvest is assumed to be the fishers' decision variable a harvesting function is not needed.

Biomass growth: $G(x,a)-q$

Management controls: Catch and discarding restrictions, (q^*,d^*). Note that d^* may be zero.

Enforcement tools: General enforcement and discarding enforcement. Enforcement of discarding restrictions may be effected in many ways with which we do not have to be concerned here. The effort on each enforcement tool is represented by the vector (e,e_d).

Cost of enforcement: $C(e,e_d)$

Penalties: Penalties for harvest violations, f_q, and for discarding f_d.

Probability of penalty: $\pi_q(e,e_d)$ and $\pi_a(e,e_d)$.

Social benefits: $B(q,d,x)-CD(d)-C(e,e_d)+\lambda\cdot(G(x)-q)$, where $CD(d)$ is the social cost of discarding e.g. because it distresses the general population.

***Private maximization*:**

The fishers' problem is:

$$\underset{z,d}{Max}\ B(q,d,x)-f_q\cdot\pi_q(e,e_d)\cdot(q-d-q^*)-f_d\cdot\pi_d(e,e_d)\cdot(d-d^*)$$

Note that this formulation of the private problem assumes that discards cannot be verified (or penalized) as catches.[5] It follows that for the fishers discarding has double benefits. It affects the benefit function directly and it reduces expected penalties for excessive catches.

The necessary conditions for solving this problem are:

[5] This assumption can of course be dropped and the modelling generalized.

$$B_q - f_q \cdot \pi_q(e,e_d) = 0 \text{, if } q>0,$$
$$B_d + f_q \cdot \pi_q(e,e_d) - f_d \cdot \pi_d(e,e_d) = 0 \text{, if } d>0.$$

In the 2nd necessary condition, note the additional benefits form discarding in terms of reduced marginal penalties, $f_q \cdot \pi_q(e,e_d)$.

Solving these equations produces the enforcement response equations:

$$q = Q(e,e_d,x,f_q,f_d,q^*,d^*),$$
$$d = D(e,e_d,x,f_q,f_d,q^*,d^*).$$

Optimal enforcement

$$\underset{e,e_d}{Max}\ B(Q(e,e_d,x,f_q,f_d,q^*,d^*),D(e,e_d,x,f_q,f_d,q^*,d^*),x) - CD(D(e,e_d,x,f_q,f_d,q^*,d^*)) - C(e,e_d)$$
$$+\lambda \cdot (G(x) - Q(e,e_d,x,f_q,f_d,q^*,d^*))$$

How to apply

To apply the above theory the following functions need to be estimated.

(5) Fishers' private benefit function including discards.
(6) A joint cost function including both enforcement efforts, $C(e,e_d)$.
(7) The two joint probability of penalty functions, $\pi_q(e,e_d)$ and $\pi_d(e,e_d)$.

(8) The social cost of discarding function *CD*(*d*). This, if not identically equal to zero, may be difficult to estimate very precisely.

In addition, the parameters, d^* and f_d as well as q^* and f_q need to be established.

Apart from this, the application of the theory proceeds in the usual way.

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