CONTROL OF FOREIGN FISHERIES

MODELLING LICENSING DECISIONS OF FISHERMEN AND THE STATE

CONTENTS:

NB: Please note that the figures in this report are not available.

INTRODUCTION

The models developed in this paper are intended to represent the decisions of a coastal state, with an Exclusive Economic Zone containing a fish stock. Foreign vessels are fishing in this zone, and the state wishes to make revenue from this fishing activity. One method to make money from the resource is to issue licences to fish to the vessels. Some vessels may not pay the licence fee, in which case the state must enforce the EEZ by capturing and penalising the illegal vessels. As a side-product of law enforcement, the state can make revenue from the penalties charged to the captured vessels. If surveillance costs are not too high, a net profit can be made from law enforcement.

Often, the fish stocks in the EEZ are also found in the open seas, or in other areas outside the jurisdiction of the coastal state. The fish stock may be sedentary, and always be found in the same area, or it may be migratory, with a definite seasonality. (In some cases the fish stock may be wholly within the EEZ of a single coastal state, although this is relatively rare. More often fish stocks are shared between coastal states.)

In order for vessels to want to fish inside the EEZ, the returns to fishing must be greater within the zone than outside, at least at some point in the year. If licence fees are set too high, it will become uneconomic to fish inside the EEZ, and the vessels will leave the zone or fish illegally. Thus the state has a set of trade-offs to consider in setting its policy on licensing. It is these trade-offs that are considered in the models set out below.

One way of considering the trade-offs is in terms of the vessels' *marginal revenues*; the difference between the income and/or profits obtained from fishing inside the zone and those obtained under other options, such as fishing on the open seas, fishing in another EEZ, or even ceasing fishing. This single parameter of marginal revenue can characterise a wide variety of different scenarios.

The rules that will govern a state's decisions about managing their coastal fishery are considered, assuming that the state wishes to maximise its profits from the fishery, given no constraints on the amount of utilization that can occur in the fishery. The model is then modified to take account of different vessel size classes and also where conservation constraints limit yields.

KEY QUESTIONS:

Fishery managers, when faced with decision-making on licensing foreign vessels (or indeed domestic vessels) will typically need to answer a number of key questions. These include include, among others:

- How many licences should be issued?
- What should a licence cost?
- What proportion of the vessels should be expected to fish illegally?
- How much money should be spent on surveillance and law enforcement?
- In a fishery with vessels that vary in size and efficiency, how should licences be allocated between vessels, and how should licences be priced in these circumstances?

In the following sections attempts are made to answer these questions, using progressively more generalised scenarios. Section 1 describes the decision rules for both fishermen and the state under two risk scenarios (neutral and prone) and when risk extends to subsequent losses following penalisation.

Section 2 describes the relationship between the control parameters of probability of capture, surveillance costs, licence costs and expected penalties. Section 3 assesses the effects on the model of different classes or categories of vessel.

Section 4 investigates an approach to licence allocation using the methods described here but with conservation constraints. Finally, section 5 describes the ways in which a Fisheries Management Game for the Control of Foreign Fisheries might be developed.

SECTION 1: DECISION RULES

1.1 FISHERMEN ARE RISK NEUTRAL - Version 1 of the Decision Rules.

First we define the areas of parameter space coinciding with (a) fishing with a licence, (b) fishing illegally and (c) fishing outside the zone or not at all. The parameters that are important are the marginal revenue; licence fee; and expected penalty incurred if the vessel fishes illegally.

The decision rules for fishermen:

- Let *MR* be the marginal revenue, in other words the difference between the expected revenue from fishing inside the licensed zone (R_L) and from fishing legally outside the licensed zone (R_U). Here *R* is the unit profit after the costs of fishing have been taken into account, and the subscripts L and U signify 'licensed' and 'unlicensed' respectively. Note that by definition $R_L > R_U$, i.e. revenues are higher inside the zone than outside. It is assumed that fishermen are prepared to pay up to the marginal revenue $(MR = R_L - R_U)$ in licence fees or penalties.

- Let *L* be the licence fee and *E(F)* be the expected penalty for fishing illegally. The term *E(F)* is the product of the fine, *F*, and the probability of being caught fishing illegally and charged, *q.*

The decision rules can be summarised as follows, first in words and then in terms of the parameters defined above:

[1A] FISHERMEN

- If the licence fee is less than the marginal revenue and less than the expected penalty then fish with a licence.

If $L \leq MR$ *and* $L < E(F)$ *then fish with a licence.*

- If the expected penalty is less than the marginal revenue and less than the licence fee then fish illegally.

If $E(F) \leq MR$ *and* $E(F) < L$ *then fish illegally.*

- If the licence fee and the expected penalty are the same and both are less than the marginal revenue then it doesn't matter -either fish illegally or with a licence.

If $L \leq MR$ *and* $E(F) \leq MR$ *and* $L = E(F)$ *then do either (licensed or illegal).*

- In all other cases, either fish legally outside the zone or not at all.

If $L > MR$ *and* $E(F) > MR$ *then fish legally (but unlicensed) or not at all.*

The areas of parameter space coinciding with the above decision rules are illustrated in Figure 1a below.

Figure 1a The parameter space defined by the fishermen's decision rules.

Note that in the third case, whatever the decision, the state does not obtain any income from these vessels. It is important to note that when conservation constraints on the total fishing effort allowed are incorporated into the model, the decision of whether to fish legally without a licence or not at all becomes very important.

***The Decision Rules for the Coastal State*:**

Assume that the state incurs a surveillance cost, *s*, in apprehending vessels carrying out illegal fishing (we assume that s is a 'per fishing vessel' surveillance cost at this stage). The net income to the state from a vessel that is caught fishing illegally is then $E(F)-s$. Now the following set of decision rules can be set up, assuming that the state is collecting revenue from the fishermen, i.e. that the licence fee and the expected penalty are less than or equal to the marginal revenue (i.e. $L \leq MR$ and $E(F) \leq MR$).

[1B] STATE

- If the licence fee is less than the expected penalty minus the surveillance cost per vessel then don't issue licences (i.e. let vessels fish illegally).

If $L < E(F)-s$ *then issue no licences.*

- If the expected penalty minus the surveillance cost per vessel is less than the licence fee then issue licences.

If $E(F)-s < L$ *then issue licences.*

- If the licence fee and expected penalty minus the surveillance cost per vessel are equal then do either.

If $L = E(F)-s$ *then do either.*

The areas of parameter space coinciding with this set of decision rules are illustrated in Figure 1b below.

Figure 1b (Unavailable) The parameter space defined by the state's decision rules.

If the two sets of decision rules are considered together, it is clear that there is only one area of 'agreement' between the state and the fishermen. This area lies between the two lines where *L=E(F)* and where *L=E(F)-s*, and coincides with fishermen wanting licences and the state wanting to issue licences (Figure 1c). At the 'edges' the state can do either (*L=E(F)-s*) and fishermen would do either (*L=E(F)*).

Figure 1c (Unavailable) The parameter space where the fishermen's and state's decision rules overlap.

It can be seen from this figure that for the state the highest possible value for the licence fee, and so the optimal value, would be to set it equal to the marginal revenue, $L^*=MR$. The optimal level of the expected penalty would also be at the marginal revenue, $E(F)^*=MR$. This would imply (in theory at least) that fishermen would be indifferent between having a licence and fishing illegally.

Licensing all vessels would be more profitable than having all vessels fish illegally, if licensing all vessels implied no surveillance cost. In practice, this may not be true since fishermen would not necessarily take up licences if they knew there would be no surveillance. This option would only be possible if there were surveillance (i.e. a non-zero probability of being caught fishing illegally) but with zero or very low cost to the state associated with it.

At this stage it is also useful to note that if a conservation constraint needs to be imposed on the number of licences that are issued, vessels that do not get licences will be fishing illegally because they are assumed to be indifferent to the choice of licence or no licence. Note that this assumption implies a neutral attitude to risk of fishermen. In version 2 of the decision rules, a risk prone attitude is considered.

1.2 FISHERMEN ARE RISK PRONE - Version 2 of the Decision Rules

It is worth considering the following question, which leads to an alternative set of decision rules: What happens as *L* or *E(F)* approaches *MR*?

It is clear that if *L=MR*, fishermen may (or may not) bother to fish under licence, because they can get the same return by fishing legally outside the zone. We can therefore assume that there would be some threshold level, say *L=aMR*, which would constitute the maximum licence fee fishermen would be prepared to pay and remain in the zone. Obviously $a \leq 1$, so this more general case includes the above set of rules. Fishermen may or may not be prepared to take risks when fishing illegally, or their perceptions of the risk of capture might be false, so that they are prepared to fish up to a proportion of *MR*, say *bMR*. If $b>1$, they are still prepared to fish illegally even if the expected penalty is larger than the maximum they would pay for a licence. If $b<1$, they are risk averse. This brings an asymmetry into the decision-making process and the modified set of rules would be:

- *If* $L \leq aMR$ *and* $L < E(F)$ *then fish with a licence*

- *If* $E(F) \leq bMR$ *and* $E(F) < L$ *then fish illegally*

- *If* $E(F) \leq bMR$ *and* $L \leq aMR$ *and* $E(F)=L$ *then do either*

- *If* $L > aMR$ *and* $E(F) > bMR$ *then fish legally outside the zone or not at all*

If we assume that the fishermen are risk prone, we assume that $a \leq b$ (because they would rather risk a penalty than pay the fee), and therefore if $L > aMR$ but $aMR < E(F) < bMR$ the fisherman would be prepared to fish illegally. Figure 1d illustrates this set of decision rules. The asymmetry associated with fishing illegally using the above set of rules is shown in the area where the licence fee is larger than *aMR* and the expected penalty is larger than the licence fee but, since the expected penalty is still less than *bMR*, fishermen are prepared to take the risk and fish illegally.

There is of course the 'special case' when *L=E(F)*. We assume that when *L=E(F)* with $L \leq aMR$ and $E(F) \leq aMR$ fishermen would be indifferent between fishing with a licence or fishing illegally.

Figure 1d (Unavailable) The decisions of a risk prone fisherman.

[2b] STATE

As before, we now consider the set of decision rules a state may use to decide whether to issue licences or not. As before, we assume a non-zero surveillance cost per fishing vessel, s. The decision rules are then:

Let $L \leq aMR$ and $E(F) \leq bMR$.

- *If $L < E(F)$-s then issue no licences (i.e. let vessels fish illegally).*
- *If $E(F)$-s $< L$ then issue licences.*
- *If $L = E(F)$ then do either.*

Figure 1e illustrates the areas of parameter space associated with the decisions for this set of rules. It is important to note that by definition of the fishermen's set of decision rules, if

$$L = aMR < E(F) \leq bMR,$$

a fisherman would want a licence but if not offered one, he would fish illegally.

Figure 1e (Unavailable) The state's decisions when the fishermen are risk prone.

When Figures 1d and 1e are put together, the area of overlap is, as before, between the lines defined by *L = E(F)* and *L = E(F)-s*. In this case, however, the maximum level for a licence fee would be $L^*=aMR$ and for an expected penalty would be $E(F)^*=bMR$ (see figure 1f).

Figure 1f (Unavailable) The overlap between the state and the fisherman.

The income to the state would then be:

Licensed: *aMR*
Unlicensed: *bMR - s*

If *a* = *b*, then the situation is the same as before, in the sense that licensing all vessels would bring in a higher income if zero surveillance cost is implied by doing so. This refinement has, however, made it clearer that this may not be practical.

If *a<b* (fishermen are risk prone), then the optimal strategy would be as follows:

- If aMR > bMR-s then licence all vessels
- If aMR < bMR-s then issue no licences
- If aMR = bMR-s then do either

The main points can be summarised as follows:

- It is only worth being in the area of 'overlap' between fishermen and a state's decisions.
- There are advantages in being in the area where fishermen can decide either way - particularly when conservation constraints enter the game.
- Some solutions may not be practical and there may be a need for reformulation of the problem or for further constraints on parameters.

1.3 EXTENDED PENALTIES - Version 3 of the Decision Rules.

In this section the decision rules are outlined for the situation where fishermen include the loss of further catches that season in their calculations of the expected penalty. Assume that the expected loss of future catches that season, due to being caught fishing illegally, can be expressed as a proportion of the expected penalty, E(F), so that the total expected penalty to the fisherman becomes (1+r)E(F).

Note that the state still only receives E(F) from a captured vessel. Also note that this case does not yet include any long term effects. It simply takes into account that fact that if a vessel is caught fishing illegally during the first month of a six-month fishing season, for example, it will not be allowed to continue fishing and will therefore lose the value of the catch the owner would have expected during the remaining 5 months.

The set of decision rules for the fisherman now becomes:

[3a] FISHERMAN

- *If $L \leq aMR$ and $L < (1+r)E(F)$ then fish with a licence.*
- *If $(1+r)E(F) \leq bMR$ and $(1+r)E(F) < L$ then fish illegally.*
- *If $(1+r)E(F) \leq bMR$ and $L \leq aMR$ and $(1+r)E(F) = L$ then do either.*
- *If $L > aMR$ and $(1+r)E(F) > bMR$ then fish outside the zone or not at all.*

The decision rules for the state remain unchanged:

[3b] STATE

Let $L \leq aMR$ and $E(F) \leq bMR$.

- *If $L < E(F)-s$ then issue no licences (i.e. let vessels fish illegally).*
- *If $E(F)-s < L$ then issue licences.*
- *If $L = E(F)$ then do either.*

SECTION 2: RELATIONSHIPS OF THE CONTROL PARAMETERS

In this section the relationships between the probability of capture, cost of surveillance, licence cost and the expected penalty are investigated.

In section 1, the expected penalty, $E(F)$, has been used without considering its two components: the probability of being caught fishing illegally, q, and the actual fine if caught, F. Also, the probability of capture was not related to the surveillance cost. In this section these two aspects are considered in more detail using version 2 of the decision rules.

We assume that the probability of detection, q, is an increasing function of the total surveillance cost:

$$q = (1-\exp(-kS)) \tag{2.1}$$

where k is the rate at which q increases with increasing S. As S (the amount spent on surveillance) increases, q (the probability of catching illegal vessels) increases less and less rapidly. Note that this function tends to 1 as S tends to infinity, i.e. if enough is spent on surveillance, all illegally fishing vessels can be caught. This may be very unrealistic and a more general formulation would be:

$$q = Q(1-\exp(-kS))$$

where $Q \leq 1$. This relationship is illustrated in figure 2a for different values of k and Q.

Figure 2a (Unavailable) The relationship between probability of capture and amount spent on surveillance.

In some cases it may be simpler to express q in terms of the 'per fishing vessel' surveillance cost, s, in which case the term kS would become kNs (where N is the number of vessels), which can be expressed as Ks.

We also assume that there is some maximum possible fine, F_{max}, which could be the value of the vessel plus the catch on board, for example. Note that this is in addition to the constraint that

$$qF = E(F) \leq bMR.$$

The constraints, from the state's point of view, are therefore:

- $L \leq aMR$ (if not, vessels won't take licences)
- $qF = E(F) \leq bMR$ (if not, vessels won't fish illegally in the EEZ, only unlicensed outside)
- $F \leq F_{max}$ (if not, vessels won't be able to pay the fine)

The 'decision area' that overlaps with that of the fishermen lies between:

$$L = qF \text{ and } L = qF - s$$

which can be transformed into a constraint on the licence fee, L:

$$qF - s \leq L \leq qF$$

If the licence fee is set between these bounds, it is in the state's interest to licence vessels and it is also in the fisherman's interest to take up a licence.

If the net income from a vessel is to be maximised, we need to maximise the following expressions:

- (a) If Licensed: $max(L)$ subject to $L \leq aMR$
- (b) If Unlicensed: $max(qF-s)$ subject to $qF \leq bMR$ and $F \leq F_{max}$.

Part (a) is straightforward; L is maximised at $L^* = aMR$ (where '*' indicates the parameter value at the optimum).

Part (b) is also straightforward with respect to F, the maximum being at $F^*=F_{max}$. Write q in terms of s (see equation 2.1) then the objective function (with F set at F_{max}) becomes:

$$Q(1-exp(-Ks))F_{max} - s$$

$$\text{subject to } Q(1-exp(-Ks))F_{max} \leq bMR$$

[See Appendix 1 for further details]

There are now two possible solutions for the optimum amount to spend on surveillance, s^*, depending on the values of the parameters. One solution is at the actual 'peak' where the first derivative is zero (figure 2b). This solution holds when

$$bMR \geq dF_{max} - 1/K \text{ and}$$

$$s^* = 1/K.Ln(dF_{max}K)$$

$$\text{implying } q^* = d(1 - 1/dF_{max}K)$$

The second solution is at the constraint (figure 2c) and holds when $bMR < dF_{max}-1/K$:

$$s^* = -1/K.Ln(1-b/dMR/F_{max}) = 1/K.Ln[dF_{max}/(dF_{max}-bMR)]$$

$$\text{implying } q^* = d(b/dMR/F_{max}) = bMR/F_{max}$$

Figure 2b (Unavailable) Internal optimum for surveillance expenditure.

Figure 2c (Unavailable) Optimum for surveillance expenditure at the constraint.

To summarise, the two solutions for the optimal surveillance effort are as follows:

SOLUTION 1:

If $bMR \geq dF_{max} - 1/K$ then

- optimal licence fee: $L^* = aMR$
- optimal fine level: $F^* = F_{max}$
- optimal surveillance cost: $s^* = 1/K.Ln(dF_{max}K)$
- optimal probability of vessel capture: $q^* = d(1-1/dF_{max}K)$

SOLUTION 2:

If $bMR \leq dF_{max} - 1/K$ then

- optimal licence fee: $L^* = aMR$
- optimal fine level: $F^* = F_{max}$
- optimal surveillance cost: $s^* = 1/K.Ln[dF_{max}/(dF_{max}\text{-}bMR)]$
- optimal probability of vessel capture: $q^* = bMR/F_{max}$

Consider how the two parts of the problem (licensed and unlicensed) compare when viewed from both the fisherman and the state's point of view. The outcomes are summarised below. Recall that L^* is the licence fee paid by a vessel (and received by the state), q^*F^* is the expected penalty paid by a vessel fishing illegally and $q^*F^* - s^*$ is the expected net penalty received by the state, after the cost of surveillance has been subtracted. Note that $q^*F^* > q^*F^* - s^*$, $L^* = aMR$ and $q^*F^* \leq bMR$.

	STATE	FISHERMAN
If fishermen risk prone (a<b):		
1) $L^* < q^*F - s^* < q^*F^*$	No Licences	Get Licence
2) $L^* = q^*F^* - s^* < q^*F^*$	Do Either	Get Licence
3) $q^*F^* - s^* < L^* < q^*F^*$	Licences	Get Licence
If fishermen risk neutral (a=b):		
4) $q^*F^* - s^* < L^* = q^*F^*$	Licences	Do Either

The decision for the fisherman is, in the first three instances, to get a licence. If not offered a licence, he would be prepared to fish illegally and hence be a potential source of revenue for the state. In the special case where *a=b*, the fisherman doesn't mind whether he fishes illegally or with a licence. If the state is only interested in licensing vessels to optimise income, it will only do so in cases 3 and 4, when the expected return per licensed vessel is greater than that from a vessel fishing illegally. In case 3, fishermen would want licences if offered but if there were a limit on the number of vessels that could be given licences, the ones that did not get licences would fish illegally. In case 4, fishermen are indifferent to fishing with a licence or illegally and it is therefore assumed that if licences were offered, they would be taken up. Note, however, that if fishermen are risk prone they may decide to fish illegally when *L* =

$q^{*}F^{*}$.

SECTION 3: THE EFFECT OF DIFFERENT CLASSES OF VESSEL

The above decision rules were formulated on the assumption that vessels fishing in the zone were all of the same size and fishing efficiency, and so the decision of a single vessel could be extrapolated to the whole fleet. This is often not true in real fisheries. In some cases, very different vessel types might be fishing in the zone, impacting to a greater or lesser extent on each other (eg purse seiners and longliners in tuna fisheries, Medley (1992)). Even if the vessels are broadly similar, they might vary significantly in Gross Registered Tonnage (GRT) (or some other measure of fishing power), and so in fishing efficiency. In these cases, a state's licensing policy will impact differently on different categories of vessel, and so the fishermen's decisions will vary between category. The decision rules are therefore generalised below to include the case of a structured fishery.

3.1 Marginal revenue to Maximum fine ratio is constant

Assume that vessels can be grouped together according to some characteristic, such as GRT or country of origin. The simplest case is as follows:

- For all categories 1...I: *a* and *b* are the same
- For each category *i*: $F_{max.i}$ and MR_i are different, but $MR_i/F_{max.i} = C$, i.e. the ratio of marginal revenue to maximum fine is constant for all *i*.

We also assume, as before, that $a < b$ and that $bMR_i < dF_{max.i} - 1/K$ for all vessel categories.

For each category i, the state's objective functions are:

- a) If Licensed: $Max\ L_i$
- b) If Unlicensed: $Max\ qF_i - s$

with constraints:

$$L_i \leq aMR_i \qquad i = 1..I$$

$$F_i \leq F_{max.i} \qquad i = 1..I$$

$$qF_i \leq bMR_i \qquad i = 1..I$$

Two points need to be noted. First, it is assumed that the probability of being caught fishing illegally is the same for all categories. This is a sensible assumption although, in some fisheries, it may be possible for surveillance to 'target' a certain type of vessel. This might be true, for example, if different types of vessels tended to fish together and in different areas, such as longliners and purse seiners in a tuna fishery. Second, it is assumed that the surveillance cost per vessel is the same irrespective of the vessel's category.

The optimal solution for this case is relatively simple when:

$bMR_i < dF_{max.i} - 1/K$: *should this be removed????*

$$s^* = -1/K.Ln(1 - Cb/Q)$$

$$q^* = Cb$$

$$F_i^* = q^* F_{max.i}$$

$$L_i^* = aMR_i$$

and the decision is made by comparing L_i^* and $q^* F_{max.i}$ - s^* for each group, and choosing the larger value. Note, however, that this is a slightly strange approach because the surveillance cost is expressed as the same value per vessel in each category. In reality, the surveillance cost is a total cost that should be subtracted from the sum of income from fines from all categories. This re-formulation is considered below, but first it is worth noting the following points with respect to the above solution.

There are two reasons why this case is relatively simple. First, the assumption that $bMR_i < dF_{max.i}\ 1/K$ implies that the maximum for each category with respect to s (or q) lies at the constraint, i.e. where $q^* F_{max.i} = bMR$. Second, the assumption that $MR_i/F_{max.i} = C$ implies that the optimal q is the same for each category. This means that the problem is easily extended from one vessel to many vessels in one category and to many categories.

At this stage we still assume that the parameters are constant within categories although there are differences between categories. This implies that the objective function for all vessels in category i can be written as follows:

- a) If all vessels are licensed: $Max\Sigma\ L_iN_i$
- b) if all vessels are unlicensed: $Max\Sigma\ qF_iN_i - sN_i$

where N_i is the number of vessels in category i. When we then sum over fleets, the objective function becomes:

- a) If all categories are licensed: $Max\ _i\ L_iN_i$
- b) if all categories are unlicensed: $Max\ _i\ qF_iN_i - sN_i$
  or $Max\ [_i\ qF_iN_i] - S$

where S is the total surveillance cost. The question that immediately arises is: what happens if some categories are licensed and others are not?

First, if $a<b$ then the maximum gross income is obtained by issuing no licences. The q-value at which this optimum occurs is the same for each fleet and is either at or below $bMR_i/F_{max.i}$. The optimal q-value is given by:

$$q^* = Q(1-1/(Qk.sF_{max.i}N_i))$$

provided that this is less than $bMR_i/F_{max.i}$ (else $q^* = bMR_i/F_{maxi}$). This implies that a 'mixture' solution will not be optimal under this set of assumptions, except when the outcome is 'do either'.

3.2 Marginal revenue to Maximum fine ratio is not constant.

The second case is one where the ratios $MR_i/F_{max.i}$ are not the same for all vessel categories. We still assume that $bMR_i < QF_{max.i}$- 1/K for all categories. Ignoring the licensing aspect for the moment and concentrating on unlicensed vessels, the first question that arises is whether it is optimal to set fines for all vessel categories at F_{max}. The following example assumes there are two categories with the following constraints:

	Category	
	A	**B**
bMR_i	100	300
$F_{max.i}$	300	600
N_i	50	50
$q_i^{\sim}$	0.33	0.50

where $q_i^{\sim}$ is the value of q_i that satisfies the constraint, $q_i^{\sim}F_{max.i} = bMR_i$.

Now assume that q is set at the minimum of the $q_i^{\sim}$ for the two categories, here 0.33, then:

CASE A

	Category A	Category B	
F_i	300 (=$F_{max.i}$)	600 (=$F_{max.i}$)	
qF_i	100 (=bMR_i)	200 (<bMR_i)	
Income	5000	10000	TOTAL=15 000

The income is calculated as $qF_i \times N_i$ (the number of vessels in the category). Now compare the situation with q set at the maximum of the $q_i^{\sim}$, i.e $q = 0.5$:

CASE B

	Category A	Category B	
F_i	200 (=$F_{max.i}$)	600 (=$F_{max.i}$)	
qF_i	100 (=bMR_i)	300 (<bMR_i)	
Income	5000	15000	TOTAL=20 000

Comparison of these two cases shows that the gross income from the two categories can be increased by setting q higher and the fine for category A below the maximum fine (F_{max}), although the expected penalty is the same in both cases. Moving from case A to case B implies an increase of 5000 income units. Therefore, it is not necessarily optimal to set the fine level for all fleets at $F_{max.i}$. It may, however, be optimal to ensure that all constraints associated with bMR_i are equal to, and not less than, bMR_i.

We know, however, that there is a cost involved in increasing q. If the gain associated with moving from the low q to the high q (5000 units in the above example) is more than the increase in surveillance cost, then it is worth increasing q. If, on the other hand, the gain is less than increase in cost, then it is not worth increasing q to the maximum of the $q_i^{\sim}$ values.

The trade-off between the gain in income and loss due to increased surveillance cost is further investigated using an example involving four categories. As before the four categories are assumed to have the following constraints and characteristics:

	Category A	Category B	Category C	Category D
bMR_i	100	200	500	1000
$F_{max.i}$	1000	1500	3000	7000
N_i	10	10	10	10
$q_i^{\sim}$	0.10	0.133	0.167	0.143

Further assume that, from equation 2.1:

$$S = -1/k.Ln(1-q)$$

where S is the total surveillance cost. The first thing to note is that the maximum the state can receive from a vessel in each of the categories is bMR_i, when $qF_i = bMR_i$ for all categories. Recall that there is effectively a single q because we assume that the surveillance cannot target a particular type of vessel.

The second thing to note is that, for a given q, the fine for fleet i either has to be at $F_{max.i}$ or below. In order to satisfy both constraints ($F_i \leq F_{max.i}$ and $qF_i \leq bMR_i$) the fine is set as follows:

$$F_i = min[F_{max.i}, bMR_i/q]$$

The gross income is always maximised when q is set at the maximum of the $q_i^{\sim}$ values. This implies (in terms of the above example) that q^*=0.167 with $F=F_{max}$ for category C. Since $q^*_i > q_i^{\sim}$ for the other categories, the fines have to be less than F_{max} in order to satisfy the constraint for bMR_i. In other words, if $q^* = max_i [q_i^{\sim}] = q_m$, where m=3 in our example, then:

$$F_m = F_{max.m} \text{ so that } q^*.F_{max.m} = bMR_m$$

and

$$(F_i = bMR_i/q^*) < F_{max.i} \text{ so that } q^*F_i = bMR_i \text{ for } i \neq m.$$

What about the net income, after surveillance has been taken into [1]account? Figures 3a and 3b illustrate the gross and net income for our example, with two different levels of the surveillance cost. In figure 3a *(K=5e-5)* the surveillance cost is relatively small and the optimal solution is q^*=0.167 (i.e. the maximum of the $q_i^{\sim}$ values). Note that the gross (and hence net) income does not increase beyond q^* because it has become uneconomic for all categories to fish in the zone.

Figure 3b *(K=3e-5)* illustrates the situation for a larger surveillance cost, for the same q as in 4a. Now the optimal solution lies somewhere between the minimum and the maximum $q_i^{\sim}$ (at about 0.145). This implies that, at the optimum, only categories with $q_i^{\sim}$ values greater than 0.145 have $F_i = F_{max}$ and $q^*F_i \leq bMR_i$. Fleets with $q_i^{\sim}$ < 0.145 have $q^*F_i = bMR$ but $F_i < F_{max}$.

Figure 3a (Unavailable) Optimal solution to the example when surveillance cost is low.

Figure 3b (Unavailable) Optimal solution to the example when surveillance cost is high.

In the above example we have assumed that each category contains the same number of vessels. If this assumption holds but the number of vessels changes, the optimal solution may also change. For example, with N_i between 4 and 13, the optimum is around q = 0.142 to 0.145, then at $N_i \geq 14$, the optimal solution becomes q = 0.167. If the number of vessels in each category changes, the optimal solution may also change drastically. For example, if there are 50 vessels in category A and only one in each of the other categories, then the optimal solution would be dominated by the values for category A. Thus the optimum is likely to be at $q^* = q_1^{\sim}$ (figures 3c and 3d).

Figure 3c (Unavailable) Optimal solution to the example with the category distribution N_i = 50,1,1,1 .

Figure 3d (Unavailable) Optimal solution to the example with the category distribution N_i = 1,50,1,1.

From the above analysis it is clear that:

- a) it is not necessarily optimal to set $F_i = F_{max}$ for all categories of vessel.
- b) The relative fleet sizes in each category affects the optimum value of q.
- c) the coefficient K that relates q to S affects the optimum value of q.

This conclusion also starts suggesting some of the difficulties that will be encountered later. If we ignore the non-linearity between *q* and *S* or assume that we can approximate it by a linear function over the range of values we are interested in, then we effectively have a linear programming problem with constraints. The problem is that we are trying to optimise with respect to the coefficients (*L, q, F*) as well as the 'allocation variables', i.e. how many of each fleet category to licence or not to licence.

What are the implications of having $q^*F_i^* < bMR_i$ for some categories, as in the example illustrated by Fig 3b? If $q^*F_i^* < bMR_i$, a fisherman would gladly fish illegally because the expected penalty is less than the maximum he is prepared to pay. Let us also assume that the fisherman is risk neutral (a=b). If the licence fee is set at bMR_i, then he will not take up the licence but rather fish illegally.

If the licence fee is set below bMR_i, the fisherman would take the licence, but the income to the state (from that particular vessel category) would be sub-optimal. However, in order to get more income from the category, more money would have to be spent to increase *q*, and the solution to the 'unlicensed' sub-problem above has shown that this is not worthwhile. This means that the maximum that can be obtained is $q^*F_i^*$, and either the categories for which $q^*F_i^* < bMR_i$ should not be licensed or they should be licensed at the reduced licence fee of $L_i = q^*F_i^*$.

From the above, the following procedure for solving the general problem seems sensible:

- 1) Optimise the 'unlicensed' problem for all categories and find q^*.
- 2) For fleets with $q^*F_i = bMR_i$, one can licence them, setting $L_i = bMR_i$. Thus the licence fee is equal to the expected fine. The state is assured the licence money, whereas the 'fine' money has an associated uncertainty, so it is better to licence than to fine, all other things being equal. However, fishermen may prefer the 'high risk' option of fishing illegally and not take up the licences offered to them (if $a<b$). For these categories it is also true that $F_i < F_{max}$. It is therefore possible to set the fine higher, eg. at F_{max}, which would imply that $q^*F_{max} > bMR_i$. This would discourage vessels from fishing illegally.
- 3) For fleets with $q^*F_i < bMR_i$, it would be necessary to let them fish illegally, since with a licence fee set at bMR_i, the fishermen would not be interested in licences. It would of course also be possible to reduce the licence fee for these categories (to $L_i = q^*F_i$) but this may be seen to be unfair and would not lead to any increase in income to the state.

If licensing all vessels implies no surveillance cost then the optimum would be to set $L_i = bMR_i$ for all fleets and to licence all vessels. Common sense, however, suggests that there should be some non-zero probability of being caught and fined for fishing illegally before fishermen would be prepared to pay for a licence, and usually this would imply that a non-zero surveillance cost is necessary even if all vessels are licensed. There may be examples where this is not true, for example in the SE Pacific.

Let's consider yet another simple example - mainly to show how one might explore the solutions given real data. Assume three categories with the following characteristics:

	Category		
	A	B	C
bMR_i	100	200	500
F_{max}	1000	1500	2000
$\tilde{q}_i$	0.10	0.133	0.25

If the vessels are licensed, the best option is to set L_i = bMR_i for each category. If we now assume a certain surveillance cost, say 2000 units, then with K=1e-4, this implies a q of 0.18. With this q, the implications for unlicensed vessels would be the following:

	Category		
	A	B	C
F_i	555	1111	2000
qF_i	100	200	360

Note that for categories A and B, qF_i = bMR_i but $F_i < F_{max}$, whereas for category C, $F_i = F_{max}$ but $qF_i < bMR_i$. This implies that vessels in categories A and B would be indifferent between being licensed or fishing illegally whereas, with L = 500 = bMR_i for category C, these vessels would choose to fish illegally. It is also clear that there is a loss of income to the state of 140 (= 500-360) units per vessel in category C at this q. If we assume for the moment that the number of vessels in each category, N_i, is the same for each category, then the net income is given by:

(3.1) $$N_i(100+200+360) - 2000 = 660N_i - 2000$$

This case can be compared with one where, say 3000 units are spent on surveillance. This implies that q = 0.259 with the following implications for each category:

	Category		
	A	B	C
F_i	386	718	1930
qF_i	100	200	500

i.e. vessels in all three categories are indifferent to whether they fish with licences or illegally. In this case the net income is given by:

(3.2) $$N_i(100+200+500) - 3000 = 800N_i - 3000$$

If we compare equations (3.1) and (3.2), we see that if $N_i \leq 7$ then (3.1) > (3.2), so it would be more profitable to spend 2000 than 3000 units on surveillance. When $N_i > 7$ then it would be more profitable to spend 3000 than 2000 units on surveillance. Figure 3e illustrates the net income for a range of values for S and N_i. This clearly shows how the optimum shifts from one level of surveillance cost (and implied q) to another as N_i changes. Note that in this example, the optimum is actually at the q implied by category C (i.e. bMR_i/F_{max} = 0.25) and so there is no point increasing q beyond 0.25.

Figure 3e (Unavailable) Income to the state as surveillance costs and numbers of vessels vary.

As before, F can be increased to F_{max} for all three categories to try to discourage vessels from fishing illegally (if there are any independent reasons for doing so). Also, if a vessel decides to fish illegally anyway (although $qF_{max} > bMR_i$), and gets caught and fined, the state would get more revenue than they bargained on!

SECTION 4: LICENCE ALLOCATION UNDER CONSERVATION

This section describes a linear programming approach to allocating licences when there is a conservation constraint with a focus on the allocation of licences to particular vessels. Consider the following scenario: It is already decided how much to spend on surveillance (i.e. S is known and so is the probability of detection, q). The levels of the licence fees and the levels of fines are also fixed. We now need to decide how many vessels to licence, and which vessels to licence. We assume that there is a distribution of vessels of different sizes.

Assume that there are I categories, and there are N_i vessels in each category i. We assume that if x_i vessels in size class i are licensed, $N_i - x_i$ vessels will be fishing illegally. This is because the licence fee and fines are set to be less than or equal to bMR_i, the proportion of marginal revenue at which the vessels leave the zone.

Let the licence fee in category i be α_i and the expected penalty $ß_i$. The income to the state would then be given by :

(4.1) $$\Sigma^I_{i=1} [\alpha_i x_i + ß_i(N_i\text{-}x_i)] - S$$

where S is the total surveillance cost. Note that it is also possible to replace the function for unlicensed vessels $(N_i\text{-}x_i)$ with a variable y_i (this will be useful later).

Equation (4.1) is the objective function, the one to be maximised to obtain the optimal policy for the state. There are, however, some constraints involved. The first set of constraints ensure that the number of licensed and unlicensed vessels does not exceed the total fleet in each category:

(4.2) $$x_i + y_i = N_i \quad i=1...I$$

We introduce a second constraint here, the conservation constraint, which limits in some way the number of fish caught. At this stage we choose to limit only the licensed effort inside the zone. Instead of simply limiting the number of vessels, we limit the number of vessel 'units'. This takes into account the fact that vessels of different sizes or characteristics often have different degrees of efficiency. The constraint for licensed vessels is therefore:

(4.3) $$\Sigma^I_{i=1} c_i x_i \leq X$$

where c_i is the relative efficiency of vessels in class i, and X is the total number of vessel units licensed. These three equations form a classical linear programming problem. We repeat them here to summarise:

Maximise:

$$\Sigma^I_{i=1} [\alpha_i x_i + ß_i y_i] - S$$

Subject to :

$$x_i \geq 0,\ y_i \geq 0,\quad i=1...I$$

$$x_i + y_i = N_i,\quad i=1...I$$

$$\Sigma^I_{i=1} c_i x_i \leq X$$

Note that the surveillance cost enters the objective function as a constant and can therefore be left out of calculations.

As indicated, this is a standard type of problem that is easily solved using the simplex method. It is, however, worth considering how the solution should look. Intuitively one would feel that categories with large licence fees should be given licences. However, this is only a good idea if their contribution to the conservation constraint is not too large. If, for example, the licence fee and expected penalty are the same for each category, i.e. $\alpha_i = ß_i$, then it doesn't really matter whether a vessel is licensed or not from the point of view of the objective function (we assume that there would be a surveillance cost even if all vessels were licensed). From the point of view of the conservation constraint, however, it would be best to licence those with relatively low efficiency, c_i.

It is therefore clear that the solution to this problem will be driven by the trade-offs between licence fees and expected penalties and the relative efficiencies of vessels. In the case where the licence fee and expected penalty are equal (i.e. where $\alpha_i = ß_i$), it is mainly the relative efficiencies that drive the solution. Note, however, that because the income from a vessel is the same whether or not it is licensed, there may be many different linear combinations of licensed and unlicensed vessels from the different categories that satisfy the conservation constraint and give the same total net income. As indicated above, it may be in the state's interest to ensure a certain amount of income from licences rather than catching vessels fishing illegally. This can be achieved by optimising only the income from licensed vessels. That implies solving the following problem:

Maximise:

$$\Sigma^{I}_{i=1} \alpha_i x_i$$

Subject to :

$$x_i \geq 0 \quad i=1...I$$

$$x_i \leq N_i \quad i=1...I$$

$$\Sigma^{I}_{i=1} c_i x_i \leq X$$

The total net income is easily calculated since $y_i = N_i - x_i$, but is the same for all combinations of licensed and unlicensed vessels for given values of S, i and $ß_i$.

SECTION 5: MODEL FOR A FISHERIES MANAGEMENT GAME

The model used in the fisheries management game uses the components explored above to produce an optimal solution for a coastal state wishing to maximise its profits from a fishery. As yet, a conservation constraint has not been included in the model. This is realistic for some fisheries (eg. the BIOT tuna fishery) but not for others. The model assumes risk neutrality in fishermen, in the absence of data suggesting that fishermen are either risk prone or risk averse (as in section 1.1). In fact there is likely to be a spectrum on attitude to risk among fishermen, as there is in the general population. A structured fishery, with one or more separate categories of vessel, is modelled (as in section 3). The data on the marginal revenues for particular categories of vessel are fed into the model, together with a value for $F_{max.i}$, αinto account both the value of the vessel and the value of the catch aboard the vessel when it is captured (as in section 1.3). A function for the relationship between the probability of capture and conviction of illegal fishermen and the amount of money spent on surveillance (as in section 2) is used to relate the amount spent on surveillance to the fishermen's decisions.

Given the assumption that $F_i = F_{max.i}$ (see Appendix 1), the model uses an iterative procedure to calculate the optimum combination of the licence fee charged and the amount of money spent on surveillance that produces the highest revenues to the state. The way in which the fishermen's decisions in the different categories change with the state's decisions on licence fee and surveillance can be illustrated. Thus the model shows the decisions taken in each category at the optimum, and how those decisions change as the parameter values change. The flexible formulation of the problem allows the user of the game fully to explore and understand the circumstances driving the optimal solution for their particular fishery.

APPENDIX 1: Detailed solution to the optimal surveillance cost problem(section 2).

The first step to solving the problem

$$\text{MAX: } Q(1-exp(-Ks))F_{max} - s$$

$$\text{SUBJECT TO: } Q(1-exp(-Ks))F_{max} \leq bMR$$

is to write the objective function as:

$$MAX: F(s,V) = Q(1-exp(-Ks))F_{max} - s + V\{bMR - Q(1-exp(-Ks))F_{max}\}$$

with constraints:

$$s \geq 0, V \geq 0$$

The (primary) Kuhn-Tucker conditions for an optimum are then:

$$\delta F/\delta V \geq 0 V(\delta F/\delta V) = 0$$
$$\delta F/\delta s \leq 0 s(\delta F/\delta s) = 0$$

This then easily leads to the two solutions given in the text. (The method must be explained here or named)

Also note that if we maximise with respect to the fine, *F,* as well, we must replace F_{max} with F in (1), and add the following conditions:

$F_{max}-F \geq 0$ and $\lambda (F_{max}-F) = 0$ (What is lambda and where does this come from????? I also changed the original Fx to Fmax)

Now if we assume that $\lambda=0$, it leads to a contradiction because the following two equalities should hold:

$$d(1-exp(-Ks))(1-V) = 0, \text{ implying } V=1$$

and

$$dKFexp(-Ks)(1-V) = 1$$

which cannot hold if the first condition is met. This implies that we cannot have $\lambda=0$, and therefore $(F_{max}-F) = 0$, so $F = F_{max}$. The rest of the solution (with respect to *s*), follows as in the above case.

APPENDIX 2: Glossary of terms.

Section 1

R_L	= Revenues obtained by a vessel fishing legally within the zone.
R_U	= Revenues obtained by a vessel fishing legally outside the zone.
MR	= Marginal increase in revenue obtained from fishing inside the zone ('marginal revenue').
L	= Licence fee charged.
$E(F)$	= Expected penalty received if vessel fishes illegally.
F	= Fine received if caught fishing illegally and charged.
q	= Probability of being caught and charged if fishing illegally.
s	= surveillance cost per vessel.
a	= maximum proportion of MR a vessel will pay as a licence fee.
b	= maximum proportion of MR a vessel will pay as an expected penalty for illegal fishing.
r	=This expected loss of fish already caught when a vessel is apprehended fishing illegally, expressed as a proportion of $E(F)$.

Section 2

S	= Total surveillance cost for whole fishery.
k	= rate of increase in q as S increases.
Q	= maximum proportion of the vessels that can possibly be apprehended fishing illegally.
N	= total number of vessels in the fishery.
K	= rate of increase in q as s increases.
F_{max}	= Maximum fine a vessel can pay.

Section 3

I	= Maximum number of categories of vessel.
i	= A particular category of vessel.
$F_{max.i}$	= Maximum fine a vessel of category i can pay.
MR_i	= Marginal revenue obtained from fishing inside the zone for category i.
C	= Ratio of MR_i to $F_{max.i}$.
L_i	= Licence fee charged to category i.
F_i	= Fine for illegal fishing paid by category i.
N_i	= Number of vessels in category i.
q_i	= Probability of being caught fishing illegally for category i.
$q_i^{\sim}$	= The value of q_i at which $q_i F_{max.i} = bMR_i$.
m	= The vessel category with the highest value of $q_i^{\sim}$.

Section 4

x_i	= number of vessels fishing with a licence in category i.
y_i	= number of vessels fishing illegally in category i.
α_i	= Licence fee in category i.
β_i	= Expected penalty in category i.
X	= Total number of vessel units that can be licensed.
c_i	= Relative efficiency of vessels in category i.
