CONTROL OF FOREIGN FISHERIES

RESEARCH REPORT

Decision modelling and the Optimisation of Benefits to Coastal State Developing Countries from the Control of Foreign Fisheries

PRODUCED BY MRAG LTD
UNDER THE
FISH MANAGEMENT SCIENCE PROGRAMME
OF THE
OVERSEAS DEVELOPMENT ADMINISTRATION

SEPTEMBER 1993

CONTENTS

1 INTRODUCTION

SUMMARY:

Objectives

The objectives of this research project were to investigate and develop methods for the assessment of optimal net benefits from the licensing of foreign vessels operating in national fisheries jurisdictions (EEZs or other extended zones). Following the development of the theoretical methodology the objective was to prepare software in the form of an analytical tool for decision making in the financial planning of surveillance and enforcement and the quantification of licence fees and penalties.

Approach

The approach was limited to theoretical investigations of the ways in which the marginal value of a nationally controlled resource (the difference between income fishing inside a zone as opposed to fishing outside a zone) could be used, in conjunction with known parameters (fish prices, catches, surveillance costs etc), to estimate the optimum combination of income, surveillance costs and the legal penalties that might apply to non-compliance.

The theoretical models developed are described in appendix 1 to this document. The computer model which puts the theoretical model into practice is described in Appendix 2.

PROJECT FRAMEWORK:

Background

Globally, the entire fisheries sector remains dominated by fleets and companies from only a few maritime nations; Japan, USSR, Korea, Taiwan, USA, Spain and France, etc. These countries possess large domestic fleets that exploit their national fish stocks either optimally or at a lowered level resulting from over-exploitation (very often with major over-capacity). Combining their domestic demand and industry structure (and other factors), these countries have expanded their activities to almost all the world's oceans. It is believed that there is little scope for major increases in catch beyond the 100 million tons currently produced.

The general movement towards unilateral extensions of marine zone sovereignty that began in the late 1970s and was finally embodied in the 1982 United Nations Convention on the Law of the Sea (UNCLOS) was a direct response to the threat by distant water fishing nations (DWFNs) to stocks of fish adjacent to countries which had their own domestic requirements or developing fishing industries. Open access to the then "common property" resources of the oceans, at least those resources close to countries which were not DWFNs, thus came to an end.

The experience of all countries to controlled access fishing has been mixed and the benefits that were presumed would accrue to individual nations and to the general health and productivity of fish stocks has remained less than satisfactory.

At the outset of the 200 nm zone era there were few frameworks or planning horizons that could be used to take control of newly acquired fish stocks to ensure sustainable conservation while securing optimum benefits from their exploitation. Most countries have, with a few exceptions, proceeded by trial and error, particularly developing countries.

This project undertook a major study of the ways in which the fleets of DWFNs and developing coastal states (CS) have responded to the new challenge of regulation of fishing on what were the high seas.

Control of Foreign Fishing in Exclusive Economic Zones

Fisheries management regimes may evolve in one of two ways; either through international agreement and cooperation or through extended fisheries jurisdiction and the application of laws and regulations of individual nation states.

History reveals that management of fisheries on an international scale is extremely complex and difficult. This has been exemplified in various international fisheries management bodies such as NEAFC, NAFO, and IWC, the performance of which has often been particularly poor primarily because of the related problems of voluntary membership and 'free riders' (Cunningham et al, 1985). Furthermore the situation of *res nullius* or *res communes* under which such management regimes exist make it almost impossible to enforce unpopular decisions.

It has now been accepted that extended fisheries jurisdiction, and the resultant 200 nm Exclusive Economic Zones, arising from the U.N. Third Conference of the Law of the Sea, constitute customary international law. The required 60 signatories is now rapidly approaching when UNCLOS becomes superseding law in those countries. It has also been generally agreed that the fishery resources within the 200 nm zones are, to all intents and purposes, the property of the adjacent coastal states. There are certain reservations and prescriptions in UNCLOS on the ways it should work for some species groups, particularly highly migratory species and straddling stocks.

Essentially, six principles underlie the provisions set out in the Convention. The most important of which is the principle of extended jurisdiction over all living and non-living resources by the coastal state (CS) within the EEZ and a territorial limit of 12 nm. The remaining principles cover management guidelines and access rights to surplus resources by geographically disadvantaged states and the management of resources in the 'high seas' beyond the EEZ's.

The move towards extended fisheries jurisdiction has had a wide-ranging set of economic impacts which are both complex and multidimensional. These include improved fisheries management, production, consumption and the welfare of coastal states and their communities, as well as various trade effects. More immediately important, it provides various benefits through systems of permitted access (usually restricted) of foreign vessels.

Coastal states opting to permit a distant water presence in their 200 nm zones are faced with several economic problems. One such problem is that of devising optimum terms and conditions of access to the coastal state to be imposed upon the distant water fleets.

Permitted access and foreign fishing

Both the CS and the DWFNs benefit from permitted access. The CS through access fees and other arrangements and the DWFNs in terms of an increased resource base available for exploitation.

Permitted access, usually involving transfer of income from the DWFN to the CS is particularly valuable to a developing country, especially if the country is unable to exploit the resource itself. Other benefits may also be realised such as receipt of foreign exchange, increased local landings and local fishery development through joint ventures. Such a joint venture recently began in Mauritania where French fishermen, exploiting langoustine stocks, faced either substantial increases in access fees, or agree to joint ventures for investment in development using the CS fishing fleet. This situation, common to many developing countries arises, more often than not, when the allocation of access rights through licence fees, contributes little in the way of economic growth and development. Indeed the so-called Second Generation Agreements currently being negotiated between the EC and developing countries are based on a move away from simple, licensing agreements towards more long term development orientated relationships.

The management and development dilemma

Developing countries have a dilemma in deciding to what extent they should develop a fishing industry of their own, or to what extent they can obtain benefits from licensing foreign fleets and permitting access of these fleets to their fish resources. Clearly, in many cases decisions about access will be taken for political reasons rather than economic ones. However, key decisions which are critical to the sensible use of both the marine resource and the scarce resources of capital in the country must be taken.

If the decision is taken to permit foreign fishing then a whole series of secondary decisions are required which involve deciding at what level to set licence fees, what amount of money is sensible to spend on compliance control (surveillance and enforcement) and what legal framework, especially the level of fines for illegal fishing.

The project was aimed at developing a suitable framework based on modern mathematical bioeconomics that answers these questions for developing countries in a practical and rigorous way. The project has first reviewed the access of foreign fleets in a number of different cases and, with the benefit of these data, developed realistic mathematical models which can be manipulated to assess what are the optimal management decisions.

General Decisions

The project has found that the data necessary to answer the questions are often available but not collected. A key result indicates that it is critically important to relate the fines for illegal fishing directly to the value or fishing power of the vessels concerned. This is so whether the decision is taken to spend large or small amounts on surveillance and seems perfectly general.

The models developed enable fisheries managers to choose the optimal combination of levels of licence fees and investments in surveillance which will maximise the benefits to the CS, but also subject to necessary conservation restraints. In the extension into the adaptive research initiative (ARI), these general models are now being applied to a wide variety of different types of fisheries. These vary from small island states dealing with heavily capitalised long-distance fishing fleets to coastal states who have a significant fishing industry and infrastructure of their own.

It has been argued (Munro 1981) that the decision to licence foreign fleets or not, is best viewed in the light of the relative costs of harvesting for domestic and foreign fleets. He showed that, in many cases, economic analysis will lead to a solution where all rights to exploit are either allocated to the domestic fleet or to foreign fleets.

In contrast, Beddington and Clark (1984) consider the allocation problem in the context of the stochastic nature of renewable resources and show that, in many situations, a mix of domestic and foreign fleets will be optimal.

STUDY RATIONALE

Maximising net benefits from resources contained within the EEZs of developing countries forms the backbone of the present study.

The study uses mathematical bioeconomic analysis and optimal control theory to investigate the relationship between the potential benefits of foreign vessel licensing and the prerequisites to effective fisheries resource management notably the cost of monitoring, control and surveillance.
A vital aspect of this project is going to be the way in which it is disseminated to appropriate fisheries managers in the developing countries. It is intended that computer software in the form of a management game will be developed and used during the dissemination of the results of the project. Overseas experience has been that such games have proved effective in getting difficult concepts across to managers. A generalised description of the management game being developed is at Appendix.

The Principle issues in the decision making process are:

- **ACCESS LICENCE BENEFITS**

What should be the level of return (licence fees) in relation to the value of the fishery and how will this be composed?

- **COST OF CONTROL**

What proportion of benefits may be deployed to ensure the fishery is properly managed?

- **PENALTIES**

What levels of penalties will be sufficient to deter illegal fishing?

In order to proceed with the research, the study was broken down in to a number of distinct areas as follows:

- **Optimal Control**

How do developing countries choose between developing their own fishing industry or licensing foreign fleets or methods of allocation between foreign fishing fleets?

- **Operations Control**

What is the interplay between the level of surveillance and its cost, the level of fines for illegal activity and the level of licence fees and the value of a licence?

- **Case Studies**

Analysis of empirical foundation of current situations derived from a case study.

- **Adaptive Research**

Take examples of three or four CS fisheries and undertake detailed analyses of their bioeconomic characteristics, including the calculation of the marginal value of licensed access (if any) to 200 nm EEZ's.

2 MODEL DEVELOPMENT

The development process for the construction of the model took a number of mathematical constructions from first principles and modified these step by step to accommodate increasingly complicated sets of different conditions to mimic the decision processes that fishermen and the state would take under a number of different scenarios.

Where any assumptions have been made about conditions or patterns of behaviour these have clearly been stated.

MODELS WITH DECISION RULES:

From the first principles in the development of the model (see below and in Appendix 1), an approach was taken to develop the model further by examining the different areas of parameter space, outlined by the terms from the mathematical expression developed from the first principles. This is because they are likely to be constrained by different sets of decision rules that would be likely to govern the behaviour of the fishermen and coastal state in different conditions. An understanding of the interaction of the variables is sought in order to determine how best to optimise the benefits or revenue to the state under different sets of parameter conditions. During the course of the research for this project there were several refinements to the development of the decision rules. (These have been outlined in a series of internal research notes produced for this project).

The construction of a number of sets of decision rules and additional modelling of the parameters around these rules was undertaken to account for factors such as:

- The relationship between probability of capture, surveillance costs and the expected penalty;
- different classes of vessels; and
- conservation constraints;
  - these were then used to provide the mathematical framework around which the model for the control of foreign fishing could be constructed. The technical details are considered in Appendix 1.

The overall approach to the model development was to construct the model from the simplest possible situation, so that it increasingly took onboard more realistic situations, i.e. from the simple decision to licence or not licence, to a situation that incorporated a risk prone attitude by the fishermen. In the next steps the relationship between probability of capture, surveillance cost and the expected penalty was explored. An expansion of the model was then undertaken to explore the likely optimisation process if more than one fishing vessel (a fleet) is considered. It was further expanded to consider optimisation outcomes if the vessels in the fishery were of different categories, size or otherwise. Lastly, conservation constraints are incorporated into the model through a linear programming approach.

For details of the mathematical construction of the models refer to Appendix 1 - Theoretical Considerations.

FIRST PRINCIPLES:

In the first stage, building upon the essential assumption that the coastal state had resources extending beyond the 200 nm zone and that the catch rates of the resource were higher inside the zone than outside the zone (and therefore desirable to DWFNs), a number of simple situations were examined from both the fishermen / vessel owner's and the state's point of view. These models can be examined in more detail in Appendix 1.

Model One

In model one it was determined in the simplest case that fishermen will want a licence if the value of the catch, minus the probability of being caught for fishing illegally, times the level of the fine is greater than the value of the catch, minus the licence fee i.e. the overall costs of compliance are lower than for poaching.

The state's income, assuming that the number of licences or unlicensed vessels are not affected by the level of the licence fee or fine, will be either from licence fees and/or from fines. Making a further assumption that outgoings are only with respect to surveillance and that the cost of surveillance increases as the probability of detecting illegal fishing increases, an expression was derived for income return to the state. The "control" variables in the expression are the licence fee, the probability of catching a poacher and the fine. As the expression is linear for both the licence fee (L) and the fine (F), the maximum return will occur when both are set at a maximum amount. However, there are likely to be realistic levels at which both of these values can be set. This expression was solved mathematically in order to maximise the income return. The probability of catching any poacher (q) will tend towards a unitary value 1 as both the fine and a parameter k (determining how fast q increases with respect to increasing cost) increase. In reality it is unlikely that the probability of capture is close to one and there will be an upper limit for q say q_{max}. Likewise there is likely to be a lower limit for q say q_{min}, if there is no surveillance then there would be no incentive for the fishermen to take up a licence. A mathematical solution for this expression shows the conditions when q is likely to tend towards $q_{max.}$

Model Two

In model two, the mathematical expression from model one was extended to include a fleet of size N which is interested in fishing in the area. The expression then contains the variables F, L, q and an additional control variable n, the number of licences. The function was then maximised with a number of realistic constraints relating to the other variables for the fine, licence fee and q. There are two possible solutions to the problem. When the two solutions are evaluated, the optimal solution is the one which gives the maximum expected income. This was done by considering the critical licence fee where the two maxima meet. The interesting feature of this model when the optimal solution is sought recommends that the solution is either all licences or no licences and not a mixture of the two. However, it does make the assumption that the fishermen all respond in the same way and the levels of L_{max} and F_{max} have been set in a sensible way.

Model Three

One of the limitations of model two is that it does not take into account the fishermen's response with respect to the taking up of licences. In model three this is modelled by assuming that the number of licences (n) that are taken up are directly related to the licence fee (L). Assuming a linear relationship between n and L then the mathematical expression developed from the previous models can be further developed to give an equation that is quadratic with respect to the licence fee, see equation 5 in Appendix 1. The unconstrained optimal solution for this equation is to set no licences.

3 GAME DEVELOPMENT

INTRODUCTION:

To illustrate the results of the theoretical research undertaken during this phase of the project, it was decided to develop a management game for use on a microcomputer. This would enable fisheries managers to experiment with the models developed in a 'hands-on' fashion. The objective was therefore to produce a game which models various types of fisheries, and allows the fishery researchers and managers to investigate the interaction between Licence costs, Surveillance costs and Fine levels, with a view to maximising state revenue.

This management game could then be used as part of a workshop to illustrate the results of this project. It is not envisaged distributing the game itself for widespread usage, but rather as a generalised management and training tool.

DATA USED:

The first version of the game is being developed using data from five fisheries:

- British Indian Ocean Territory Tuna Fishery.
- Namibia Mid-Water Trawl Fishery
- Falkland Island Squid Fishery.
- Seychelles Tuna Fishery.
- South Pacific Tuna Fishery

HARDWARE/SOFTWARE:

The 'Quattro Pro for Windows' spreadsheet package is used which runs on 80386 and 80486 IBM-compatible personal computers. The logic of the game was written using 'Turbo Pascal for Windows' and incorporated into 'Quattro Pro' using the add-in function toolkit supplied by the manufacturers, Borland.

FORMAT OF THE GAME:

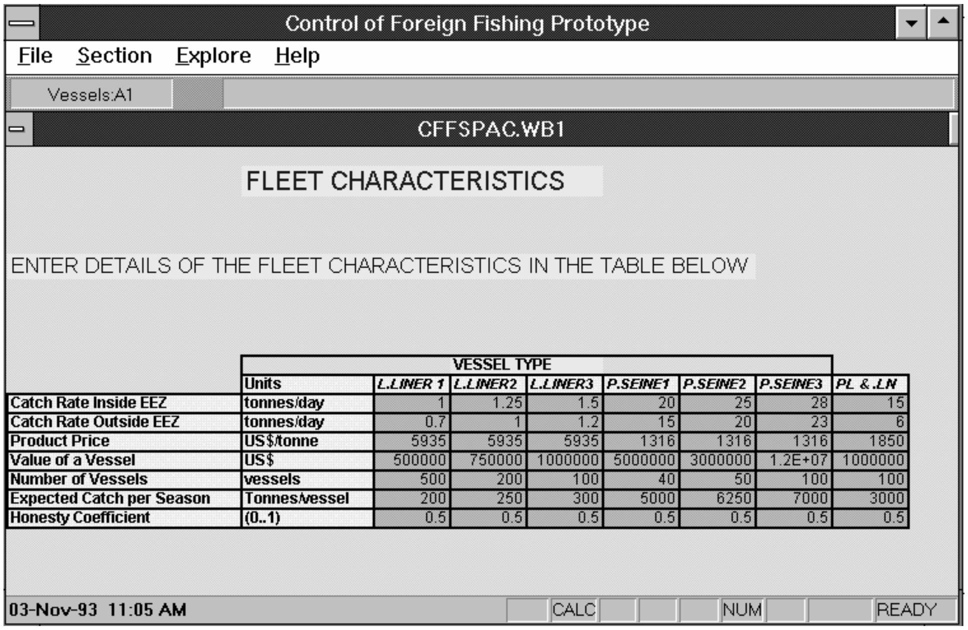
This method enables users to enter data in a familiar front-end environment which can itself use the power of Turbo Pascal to undertake the model optimisation calculations quickly and efficiently, producing quantitative output that can be viewed and printed by pages of the Quattro Pro notebook. Quattro Pro uses a 'notebook' metaphor for arranging its data and this suited the game's needs very well, with each section of the game being stored on a separate 'page' within the notebook. Quattro Pro's user interface controls are used to enable users to quickly move from one page to another.

PRINCIPAL GAME PAGES:

The main pages incorporated in the system are as follows:

■ Fleet Characteristics

This page is used to specify the characteristics (static and operational) of the vessels exploiting a particular fishery. The example given below is an approximation of the South Pacific Tuna Fishery:



FLEET CHARACTERISTICS

ENTER DETAILS OF THE FLEET CHARACTERISTICS IN THE TABLE BELOW

		VESSEL TYPE						
	Units	L.LINER 1	L.LINER2	L.LINER3	P.SEINE1	P.SEINE2	P.SEINE3	PL & .LN
Catch Rate Inside EEZ	tonnes/day	1	1.25	1.5	20	25	28	15
Catch Rate Outside EEZ	tonnes/day	0.7	1	1.2	15	20	23	6
Product Price	US$/tonne	5935	5935	5935	1316	1316	1316	1850
Value of a Vessel	US$	500000	750000	1000000	5000000	3000000	1.2E+07	1000000
Number of Vessels	vessels	500	200	100	40	50	100	100
Expected Catch per Season	Tonnes/vessel	200	250	300	5000	6250	7000	3000
Honesty Coefficient	(0..1)	0.5	0.5	0.5	0.5	0.5	0.5	0.5

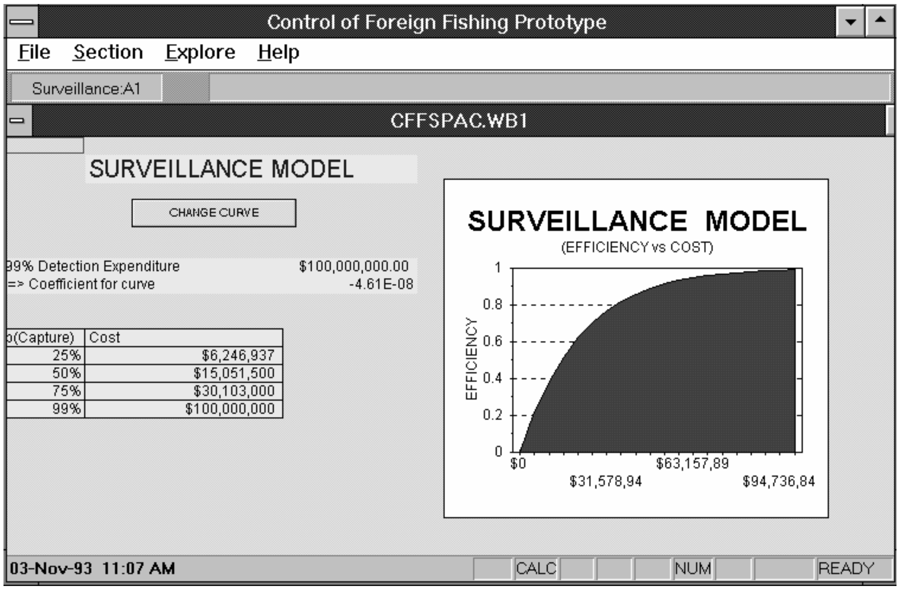
03-Nov-93 11:05 AM

In this example, there are three categories of both longliners and purse-seiners, and one category of pole and line vessels. The management game model can, in fact, be built with any number of vessel categories including subdivisions by nation. For the purpose of this game, a fleet category is a group of vessels with similar catching capabilities and economic overheads.

This table must contain all the information required to calculate expected revenue fishing either inside or outside the given Exclusive Economic Zone. Given this information and levels for surveillance, penalties and licences, it is possible to calculate expected revenue for each vessel category in the table. The user enters the information from other sources, perhaps including estimates close to reality where detailed analytical figures are not available.

■ Surveillance Model

This page is used to specify the relationship between surveillance expenditure and the probability of detection.



SURVEILLANCE MODEL

99% Detection Expenditure $100,000,000.00
=> Coefficient for curve -4.61E-08

(Capture)	Cost
25%	$6,246,937
50%	$15,051,500
75%	$30,103,000
99%	$100,000,000

The probability distribution can be altered by changing the parameters supplied to the surveillance function.

■ Optimisation

Once fleet characteristics have been defined, the game proceeds with a routine that will optimise surveillance costs, licence fees and fine levels in order to maximise state revenue. To do this, it uses the economic information supplied to estimate the expected revenue from the following three situations:

_ Fishing legally inside the EEZ

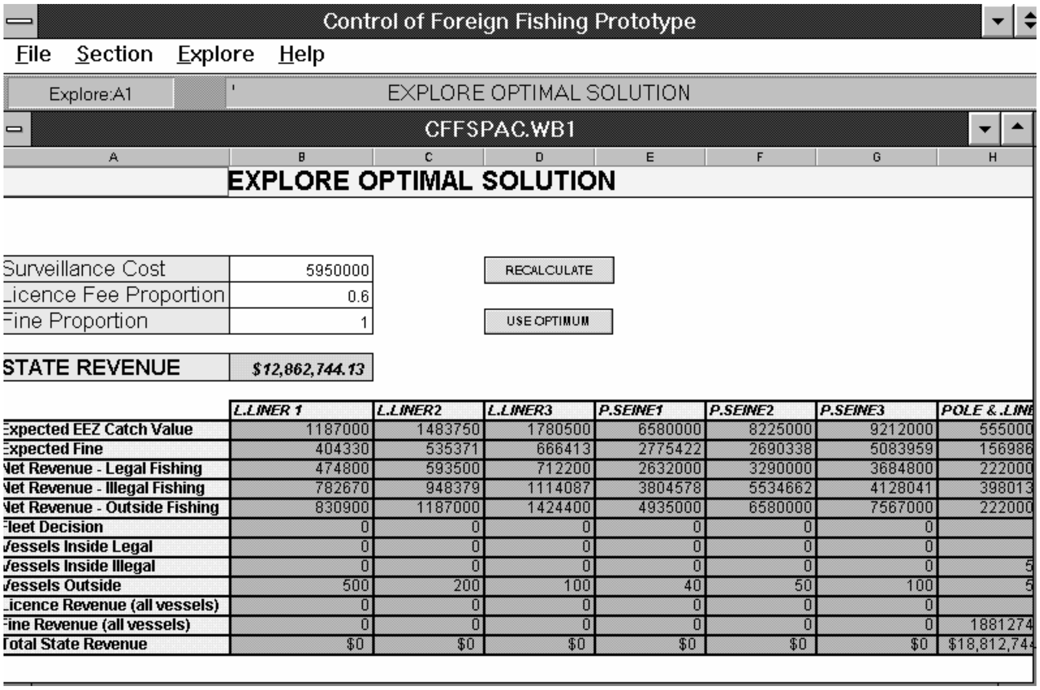
_ Fishing illegally inside the EEZ

_ Not fishing in the EEZ at all

For each fleet category the model calculates which of these three situations would be the most profitable to the fleet and then assumes that all vessels in the category will pursue this activity. In the case where there is a choice between legal and illegal fishing as first and second most profitable activities, an 'honesty coefficient' is included which determines what proportion of vessels within a category would not fish illegally irrespective of whether it is the most profitable activity.

- **Exploration of Optimum Solution**

Once the model has found the optimum levels for the three parameters in order to maximise revenue, this page enables the user to see how revenue alters as these parameters are varied around the optimum value. The figure below illustrates the variables upon which the fleet decisions are made.



EXPLORE OPTIMAL SOLUTION

Surveillance Cost	5950000
icence Fee Proportion	0.6
ine Proportion	1

STATE REVENUE	*$12,862,744.13*

	L.LINER 1	*L.LINER2*	*L.LINER3*	*P.SEINE1*	*P.SEINE2*	*P.SEINE3*	*POLE & .LIN*
xpected EEZ Catch Value	1187000	1483750	1780500	6580000	8225000	9212000	555000
xpected Fine	404330	535371	666413	2775422	2690338	5083959	156986
let Revenue - Legal Fishing	474800	593500	712200	2632000	3290000	3684800	222000
let Revenue - Illegal Fishing	782670	948379	1114087	3804578	5534662	4128041	398013
let Revenue - Outside Fishing	830900	1187000	1424400	4935000	6580000	7567000	222000
leet Decision	0	0	0	0	0	0	
essels Inside Legal	0	0	0	0	0	0	
essels Inside Illegal	0	0	0	0	0	0	5
essels Outside	500	200	100	40	50	100	5
icence Revenue (all vessels)	0	0	0	0	0	0	
ine Revenue (all vessels)	0	0	0	0	0	0	1881274
otal State Revenue	$0	$0	$0	$0	$0	$0	$18,812,74

4 CONCLUSIONS AND RECOMMENDATIONS

This draft report provides the basis for review by persons working in similar fields. It is therefore submitted to them prior to the detailed formulation of conclusions and recommendations. However, for current purposes the following conclusions and recommendations are made:

RESEARCH NEEDS:

Conclusions

The management dilemma in developing countries that are subject to pressure, or have the desire to enter into licensing agreements with individual fishing vessels or Distant Water Fishing Nations, is pressing. There is general dissatisfaction in developing countries with the levels of resource rents obtained, and uncertainty over decisions about the need to apply surveillance costs (as a necessary proportion of income) and the appropriateness of penalties for unlicensed fishing.

Recommendations

Research, using case studies, should be undertaken in a limited number of states (or regions) to assess the need for its extension under the Adaptive Research Initiative.

OBJECTIVES:

Conclusions

This research, probably the first of its kind in the world, has attempted to develop a methodology from first principles that will allow fishery managers and operations researchers in the fisheries field to investigate the effects of decision making processes in the licensing. Research achieved so far indicates that it is possible to make sensible decisions based on the modelling, and that a useful method in the decision making process is the development of a management game.

Recommendations

Using the case studies, demonstrate that the methodology works in the target states in specifically adapted form.

OUTPUT:

Conclusions

The model output, as produced through the management game, indicates that reasonable results can be achieved from the model.

Recommendations

Collect further data and receive views of target countries on their needs for model output and results presentation.

BIBLIOGRAPHY

Anderson L. G., (1989). Enforcement issues in Selecting Fisheries Management Policy. Marine Resource Economics Vol, 6 pp 261-277, 1989.

Anderson L.G., (1987). Expansion of the Fisheries Management Paradigm to Include Institutional Structure and Function. Transactions of the American Fisheries Society 116 : 396-404, 1987.

Anderson L. G., (1987). A Management Agency Perspective Perspective of the Economics of Fisheries Regulation. Marine Resource Economics, Vol 4, pp 123-131, 1987.

Anderson L. G., (1987). Bridging the Gap Between Economic Theory and Fisheries Management: Can the MFCMA Produce Economically Rational Management? Marine Fisheries Review 49 (3) 1987.

Anderson L.G., (1987). Production Function for Fisheries : Comment. Reprint from Southern Economic Journal Vol 44, No 3, Jan 1987.

Anderson L. G. & Lee D. R., (1986). Optimal Governing Instrument, Operation Level, and Enforcement in Natural Regulation : The Case of a Fishery. American Journal of Agricultural Economics Vol 68, No3, August 1986.

Anderson L. G., (1985). Potential Economic Benefits from Gear Restrictions and License Limitation in Fisheries Regulation. Land Economics Vol 61, No 4, November 1985.

Anderson L. G., (1983). The Demand Curve for Recreational Fishing with an Application to Stock Enhancement Activities. Land Economics Vol 59 No 3 Aug 1983.

Anderson L. G., (1982). Optimal Utilization of Fisheries with Increasing Costs of Efforts. Canadian Journal of Fisheries and Aquatic Sciences Vol 39 No 1 1982.

Anderson L. G., (1982). Optimum Effort and Rent Distribution in the Gulf of Mexico Shrimp Fishery: Comment. American Journal of Agricultural Economics Vol 64, No 1 Feb 1982.

Anderson L. G., (1982). Optimal Intra and Inter-seasonal Harvesting Strategies when Price Varies with Individual Size. Marine Resource Economics Volume 6, pp 145-162.

Anderson L. G., (1981). Necessary Components of Economic Surplus in Fisheries Economics.
Can J Fish Aquat Sci, 37 : 858-870.

Andersen, P., (1985). Fisheries Law Enforcement and Transferable Individual Quotas: A Tentative Analysis. In Fisheries Law Enforcement: Programs, Problems and evaluation. proceedings of a workshop on fisheries law enforcement, University of Rhode Island Oct 21-23 1985.

Applications of Satellite Remote Sensing Over the Indian Ocean. A manual prepared by the Organisation for Indian Ocean marine Affairs Co-operation (IOMAC) August 1991.

Beddington, J. R. and Basson, M. (1991). Allocation between National and Foreign Fishing Fleets: the Falklands Islands Squid Fishery. Unpublished Report.

Bonucci, N., (1992). Regional Workshop on Monitoring, Control and Surveillance for African States Bordering the Atlantic Ocean. FAO/Norway : Fisheries Management and Law Enforcement Advisory programme, 1992. Legal and policy Issues Related to Monitoring, Control and Surveillance.

Brown, C. (1992). Requirements for Effective Sub-Regional Cooperation in Monitoring, Control and Surveillance: The Pacific Experience. FAO/Norway : Fisheries Management and Law Advisory Programme.

Caddy J. F., (1982). Some Considerations Relevant to the Definition of Shared Stocks and Their Allocation between Adjacent Economic Zones. FAO Fisheries Circular No 749. FIRM/C749. FAO, Rome, 1982.

Clarke, F .H. and Munro, G. R. (1991). Coastal States and Distant Water Fishing Nations : Conflicting Views of the Future. Natural Resource Modelling, Vol.5 No.3.

Commission of the European Communities, 1991. Study of the Use of a Satellite-Based Monitoring System for the Fishing Activities of the Community Member States.

Development of International/Regional Co-operation in Fisheries Monitoring Control and Surveillance. Commonwealth Secretariat. TP/EEZ/1

Doulman, D. J., (1992). Regional Workshop on Monitoring, Control and Surveillance for African States Bordering the Atlantic Ocean. FAO/Norway : Fisheries Management and Law enforcement Advisory programme, 1992. Fisheries Management, Monitoring, Control and Surveillance and Economic Considerations.

Doulman D. J. & Terawasi P., (1990). The South Pacific Regional Register of Foreign Fishing Vessels. Marine Policy July 1990.

Evans D., (1987). Fisheries Information and Surveillance : Increasing the Likelihood of Encounters. Forum Fisheries Agency. FFA Report No 87/39

FAO, (1992). Regional Workshop on Monitoring, Control and Surveillance for African States Bordering the Atlantic Ocean. FAO/Norway : Fisheries Management and Law enforcement Advisory programme, 1992.

FAO, (1992). Regional Workshop on Monitoring, Control and Surveillance for African States Bordering the Atlantic Ocean. FAO/Norway : Fisheries Management and Law enforcement Advisory Programme, 1992. Overview of the Fisheries Situation with Respect to Monitoring, Control and Surveillance for African States Bordering the Atlantic Ocean.

FAO, (1989). Contribution of Remote Sensing to Marine Fisheries. 12th UN/FAO International Training Course in Cooperation with Government of italy, Rome, Italy, 11-30 May 1987. RSC Series 49. Rome 1989.

FAO, (1988). Coastal State Requirements for Foreign Fishing. Legislative Study No 21, Rev 3. FAO, Rome, 1988.

FAO, (1985). Control over Fisheries in the Exclusive Economic Zone of the Republic of the Cape Verde Islands. C.H.Newton. CVI/82/003/TECH/REP/13 (En). FAO Rome 1985.

FAO, (1983). Report of the Expert Consultation on the Conditions of Access to the Fish Resources of the Exclusive Economic Zones. FAO Fisheries Report No 293. FIPP/R293, Rome 11-15 April 1983.

FAO, (1981). Report on an Expert Consultation on Monitoring, Control and Surveillance Systems for Fisheries Management. FAO/GDP/INT/344/NOR. FAO/NORWAY Cooperative Programme, Rome, Italy, 27-30 April 1981.

FAO, (1981). Management of Fisheries in the Exclusive Economic Zone. FAO EEZ Programme. A report prepared for the Ministry of Fisheries of the Government of the Maldives. Francis T. Christy; Lawrence C. Christy; W. Perry Allen and Robin Nair. FI GCP/INT/334/NOR and GCP/RAS/087/NOR. FAO Rome 1981.

FAO, (1981). Report of the Consultation on Monitoring Control and Surveillance. Interregional fisheries development and management programme. CECAF/TECH/81/35 (En) FAO October 1981

FAO, (1981). Monitoring, Control and Surveillance. Report of the Regional Seminaron Monitoring, Control and Surveillance of Fisheries in the EEC. SCS/GEN/81/31/ 1981

FFA, (1982). Fisheries Access Rights Negotiations. Workshop convened at the Cultural Centre Hall, Port Vila, Vanuatu. 23 Sept - 1st Oct 1982. Forum Fisheries Agency : Report of Proceedings.

Gulland J. A., (1980). Some Problems of the Management of Shared Stocks. FAO Fisheries Technical Paper No 206. FIRM/T206. FAO, Rome 1980.

Haywood, K. H. and Curr, C.T.W. (1984). Economic Evaluation of the Purse Seining Industry. FAO Fisheries Circular No. 751, Revision 1.

Huppert D .D., (1991). Managing the Groundfish Fisheries of Alaska : History and Prospects. Reviews in Aquatic Sciences. 4 (4) : 339-373 (1991)

Jennings M. G., (1981). Surveillance and Control of Marine Resources. Paper delivered to a Management Workshop by the Seafish Industry Authority, Hull, 1981.

Jennings M. G., (1980). The Enforcement of Fisheries Regulations. CECAF/TECH/80/22 (En). FAO 1980.

Kaczynski V. M., (1989). Foreign Fishing Fleets in the sub-Saharan West African EEZ : The costal state perspective. Marine Policy January 1989

Lepiz, L. G. & Sutinen J. G., (1985). Surveillance and enforcement operations in the Costa Rican tuna fishery. Marine Policy October 1985.

Marking of Fishing Gear. Fishery Committee for the Eastern Central Atlantic. Twelfth Session Accra, Ghana, 24-28 February 1992

Moore G., (1987). Enforcement without force : New concepts in compliance control for foreign fishing operations. The Law of the Sea, FAO 1987.

Queirolo L. E. & Johnston R. S., (1989). Distant water fishing nations and extended fisheries jurisdiction. Marine Policy January 1989.

Rackowe R., (1981). Preliminary Information Requirements of Potential Foreign Investors in Industrial Fishing Ventures. Fisheries Circular No 831 FIP/C831

Russel, S. C. (1990). Game Models for Structuring Monitoring and Enforcement systems. Natural Resource Modelling, Vol. 4 No. 2.

Sutinen J. G., & Gauvin J. R., (1989). Assessing Compliance with Fishery Regulations. Maratimes Vol. 33 No. 1.

Sutinen J. G., & Gauvin J. R., (1989). An Econometric Study of Regulatory Enforcement and Compliance in the Commercial Inshore Lobster Fishery of Massachussets. In P.A.Neher et al (eds) Rights Based Fishing, 415-428 1989. Kluwer Academic Publishers.

Sutinen J. G., (1988). Enforcement Economics in Exclusive Economic Zones. GeoJournal 16.3 273-281.

Sutinen J. G. & Anderson, P., (1985). The Economics of Fisheries Law Enforcement. Land Economics Vol 61 No 4.

Sutinen J. G., Rieser A., & Gauvin J. R. Measuring and Explaining Noncompliance in Federally Managed Fisheries. Ocean Development and International Law, Vol. 21 pp 335-372.

Ulfstein G., Anderson P. & Churchill R., (1986). The Regulation of Fisheries : Legal, economic and social aspects. Proceedings of a European workshop. University of Tromso, Norway, 2-4 June 1986.

Underwood, P. Expanded maritime Jurisdiction: New Prospects for the West African Fisheries. Oceans Institute of Canada.

APPENDIX 1 : THEORETICAL CONSIDERATIONS

PROJECT: CONTROL OF FOREIGN FISHERIES

MODELLING LICENSING DECISIONS OF FISHERMEN AND THE STATE

CONTENTS:

ANNEX 2: **Glossary of terms**

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 fishing licences 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, 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.

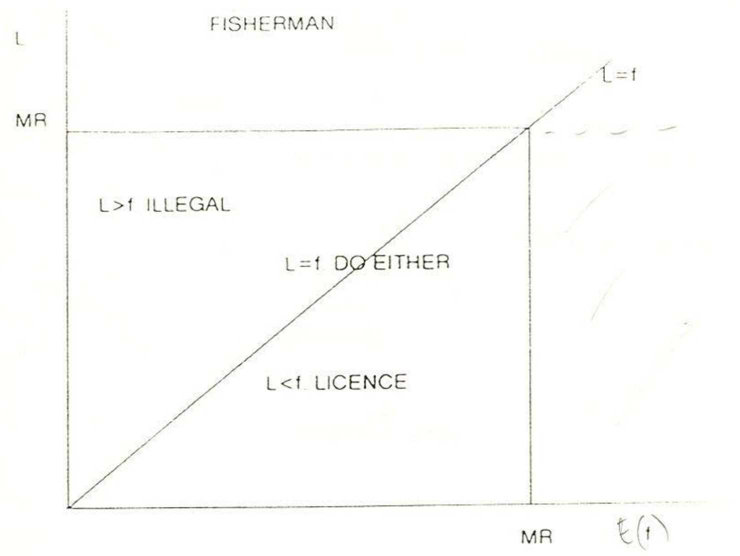


Figure 1a The parameter space defined by the fishermen's decision rules.

Note that in the last case, whatever the decision, the state does not obtain any income from these vessels. It is important to note however 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.

I*f 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.

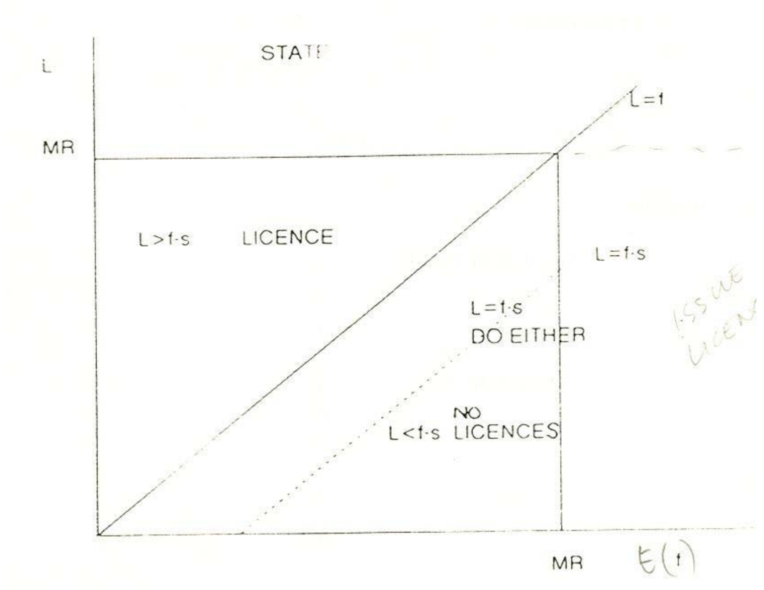


Figure 1b The parameter space defined by the state's decision rules.

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)*).

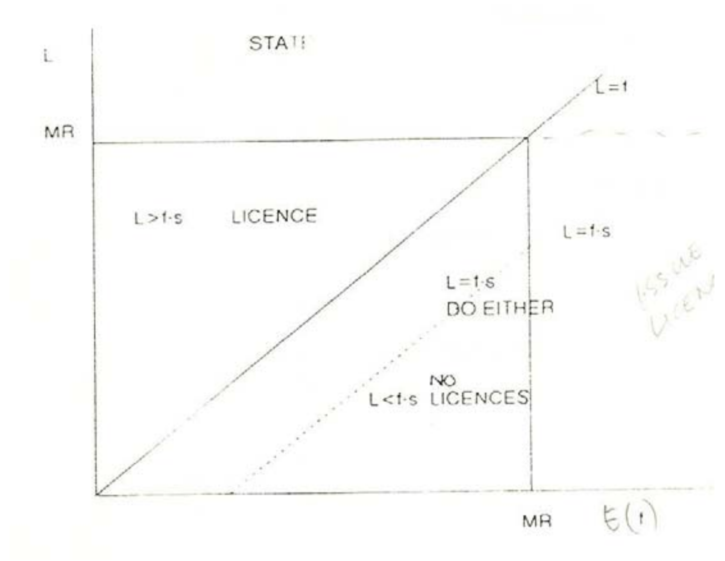


Figure 1c The parameter space where the fishermen's and state's decision rules overlap.

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 $E(F) \leq bMR$ fishermen would be indifferent between fishing with a licence or fishing illegally.

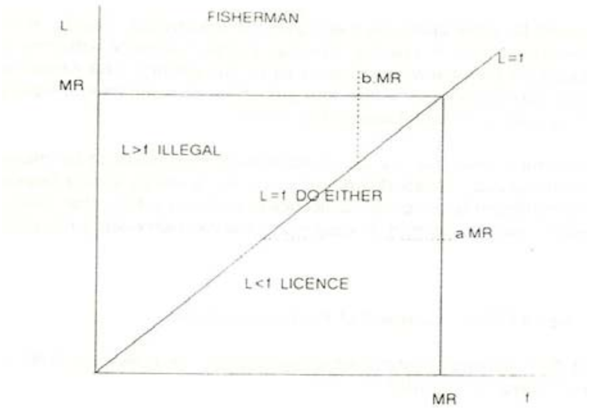


Figure 1d The decisions of a risk prone fisherman.

[2b] STATE

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.

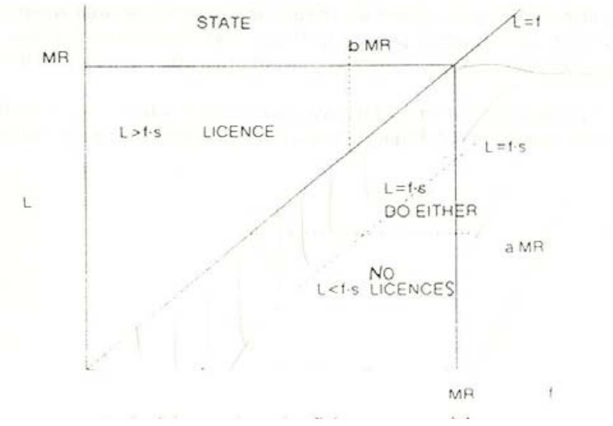


Figure 1e The state's decisions when the fishermen are risk prone.

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).

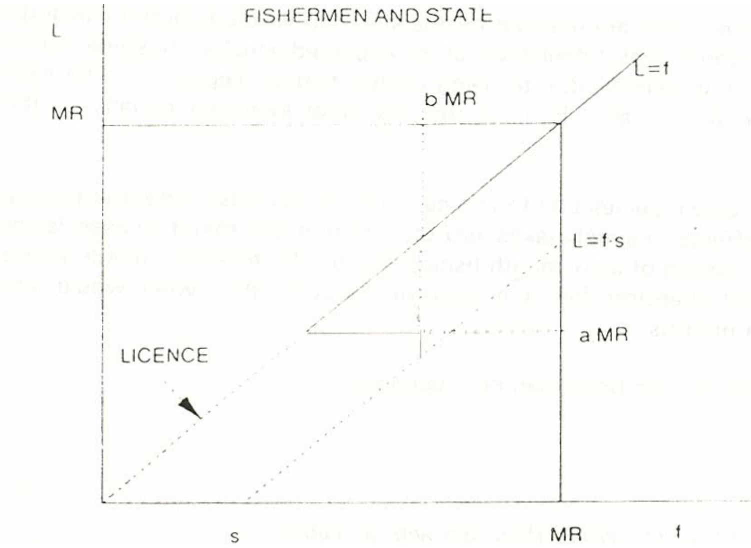


Figure 1f The overlap between the state and the fisherman.

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 picture.
- 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 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:

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

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:

(2.1) $q = Q(1-\exp(-kS))$ [where *d* has been replaced by *Q*]

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

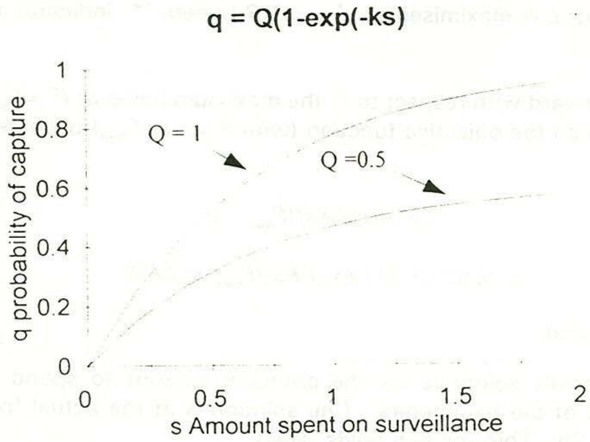


Figure 2a The relationship between probability of capture and amount spent on surveillance.

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

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

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

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

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

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

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

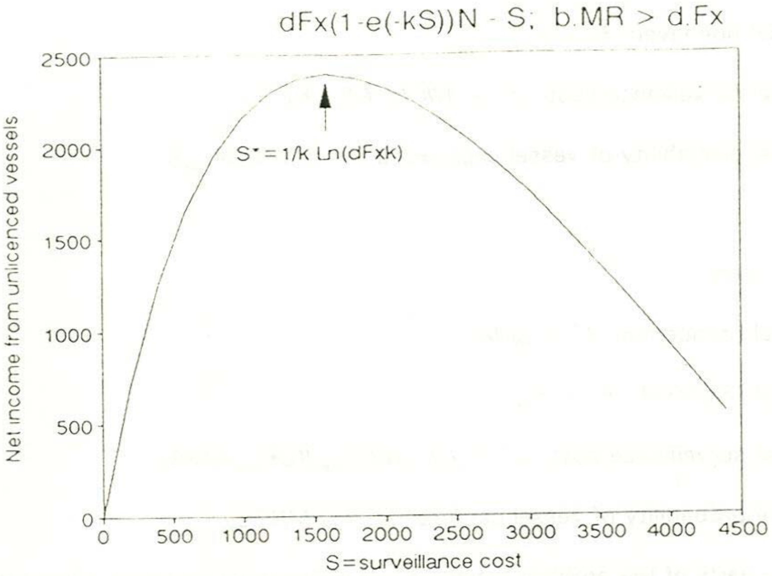


Figure 2b Internal optimum for surveillance expenditure.

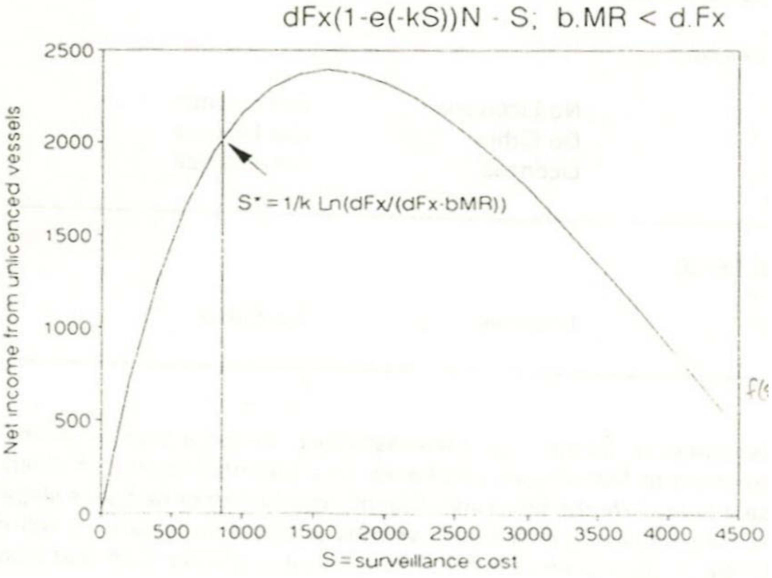


Figure 2c Optimum for surveillance expenditure at the constraint.

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

SOLUTION 1:

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

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

SOLUTION 2:

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

- optimal licence fee: $L^* = aMR$
- optimal fine level: $F^* = F_{max}$
- optimal surveillance cost: $s^* = 1/K.Ln[QF_{max}/(QF_{max}-bMR)]$
- 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, such that: $bMR_i < dF_{max.i} - 1/K$. The optimal solution for this case is relatively simple:

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

$$q^* = Cb$$

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

$$L_i^* = aMR_i$$

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 $bMR_i < QF_{\mathrm{max.i}} - 1/K$ 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: $Max\ L_iN_i$
- b) if all vessels are unlicensed: $Max\ qF_iN_i - sN_i$

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: $Max\ \Sigma_i\ (L_iN_i)$
- b) if all categories are unlicensed: $Max\ \Sigma_i\ (qF_iN_i - sN_i)$
  or $Max\ \Sigma_i\ (qF_iN_i) - S$

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:

$$q^* = Q(1-1/(Qk.s\Sigma F_{max.i}\, N_i))$$

provided that this is less than $bMR_i/F_{max.i}$ (else $q^* = bMR_i/F_{max.i}$). 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 $\tilde{q_i}$ 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 $\tilde{q_i}$, 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 ($F_{max.i}$), 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 $\tilde{q_i}$ 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
$\tilde{q_i}$	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 $F=F_{max.i}$ for category C. Since $q^*_i > q_i^{\sim}$ for the other categories, the fines have to be less than $F_{max.i}$ in order to satisfy the constraint for bMR$_i$. In other words, if $q^* = max_i\,[q_i^{\sim}] = q_m$, where m=3 (the 3rd category) 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 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 3a. 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 $F_i < F_{max}$.

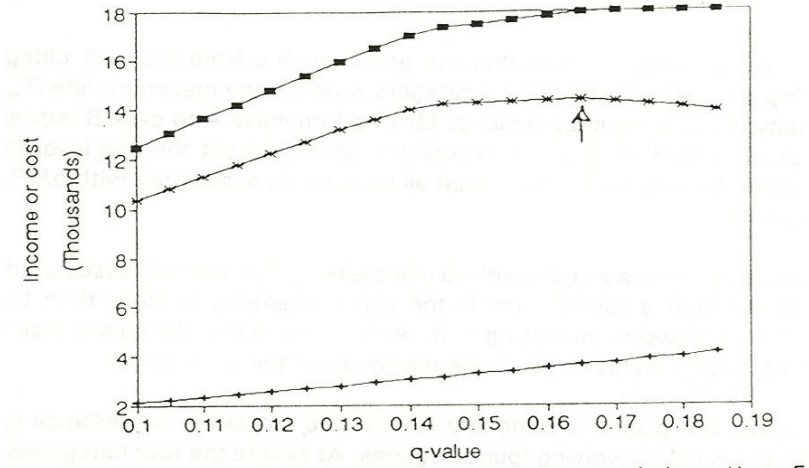


Figure 3a Optimal solution to the example when surveillance cost is low. ($k = 5e^{-5}$)

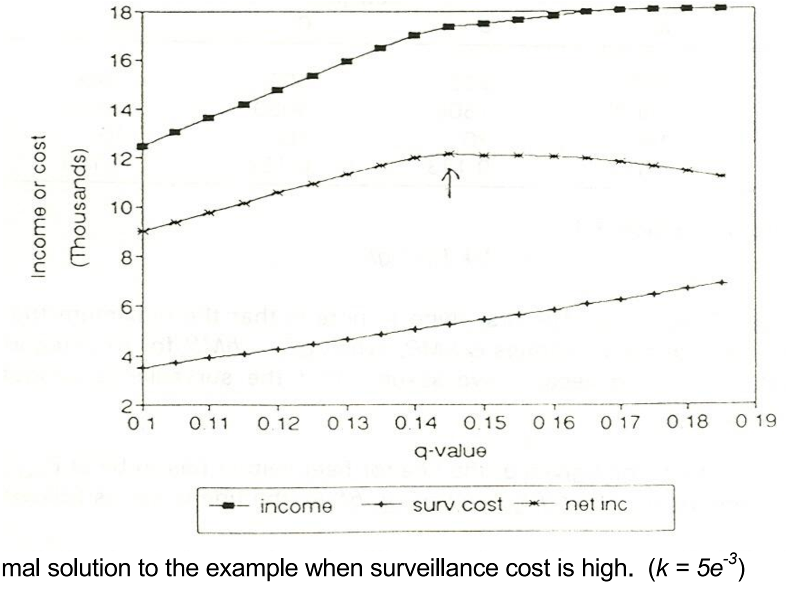


Figure 3b Optimal solution to the example when surveillance cost is high. ($k = 5e^{-3}$)

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).

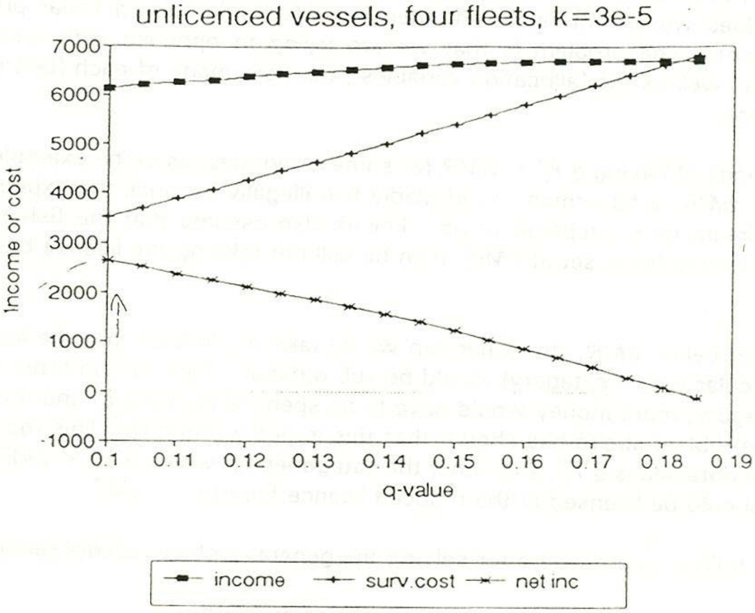


Figure 3c Optimal solution to the example with the category distribution N_i = 50,1,1,1 .

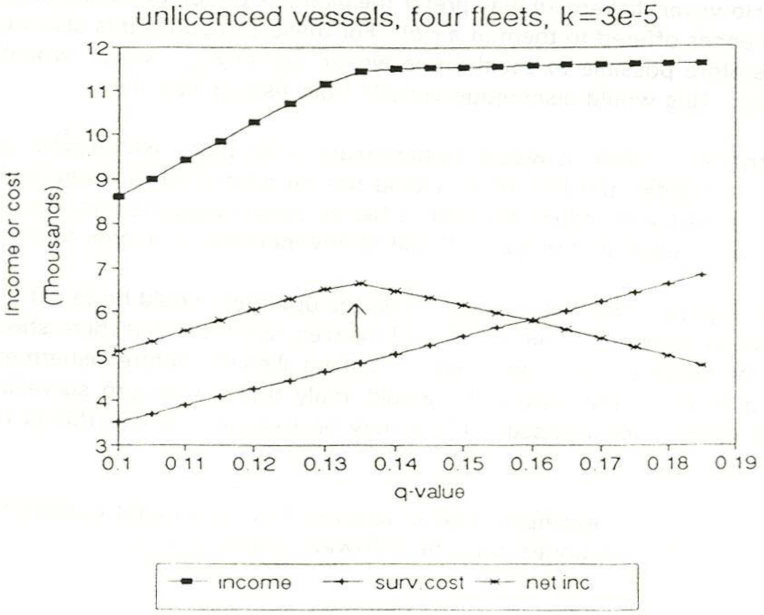


Figure 3d Optimal solution to the example with the category distribution N_i = 1,50,1,1.

From the above analysis it is clear that:

- a) it is not necessarily optimal to set $F_i = F_{max.i}$ 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:

- Optimise the 'unlicensed' problem for all categories and find q^*.

- 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 $F_i < F_{max.i}$. It is therefore possible to set the fine higher, eg. at $F_{max.i}$, which would imply that $q^*F_{max.i} > bMR_i$. This would discourage vessels from fishing illegally.

- 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
$F_{max.i}$	1000	1500	2000
$q_i^{\sim}$	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 $F_i < F_{max.i}$, whereas for category C, $F_i = F_{max.i}$ 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:

$$N_i(100+200+360) - 2000 = 660N_i - 2000 \tag{3.1}$$

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

$$N_i(100+200+500) - 3000 = 800N_i - 3000 \tag{3.2}$$

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 for category C (i.e. $bMR_i/F_{max} = 0.25$) and so there is no point increasing q beyond 0.25.

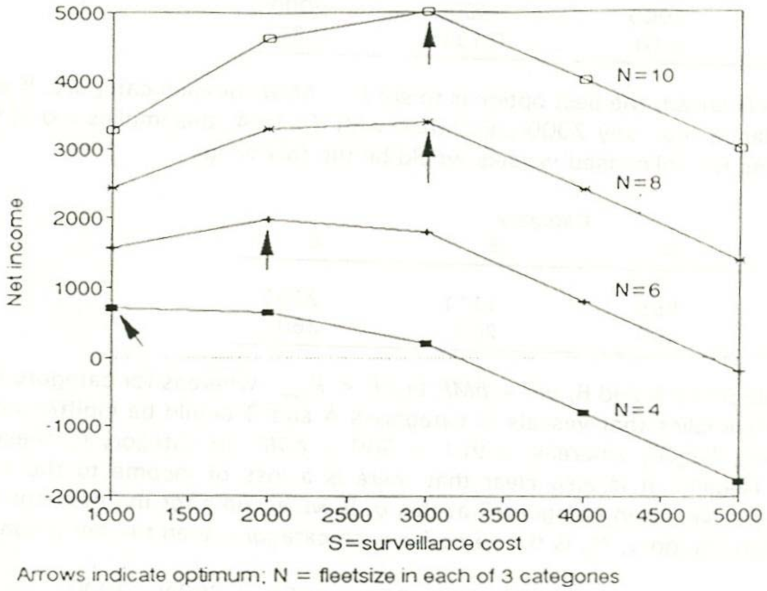


Figure 3e Income to the state as surveillance costs and numbers of vessels vary.
(Arrows show the optima. N_i = number of vessels in each category)

As before, F_i can be increased to $F_{max.i}$ 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 $qF_{max.i} > bMR_i$), 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 β_i. The income to the state would then be given by :

$$\Sigma^{I}_{i=1} [\alpha_i x_i + \beta_i(N_i - x_i)] - S \tag{4.1}$$

where *S* is the total surveillance cost. Note that it is also possible to replace the function for unlicensed vessels (N_i-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 ensures that the number of licensed and unlicensed vessels does not exceed the total fleet in each category:

$$x_i + y_i = N_i \qquad i=1...I \tag{4.2}$$

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:

$$\Sigma^{I}_{i=1} c_i x_i \leq X \tag{4.3}$$

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:

$$\Sigma^{I}_{i=1} [\alpha_i x_i + \beta_i y_i] - S$$

Subject to :

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

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

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

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 of 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 $F_{max.i}$, taking into 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.

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

The problem considered here falls into the category of nonlinear programming problems in the field of operations research. The approach is refered to as Kuhn-Tucker Analysis. For further reading, see (for example) Baumol (1972).

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:

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

(Note: *V* plays a similar role here as Largrange multipliers play in Lagrangian analysis.)

This then easily leads to the two solutions given in the text using methods described in Burges, *'Introduction to Control Theory including Optimal Control'* .

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

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

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:

$$F_{max}-F \geq 0 \text{ and } V(F_{max}-F) = 0$$

Where *V* is similar to a Lagrange multiplier, $V \geq 0$

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

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

and

$$QKF\exp(-Ks)(1-V) = 1$$

which cannot hold if the first condition is met. This implies that we cannot have *V=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.

Ref:Baumol, W.J. 1972. Economic Theory and Operations Analysis. Prentice Hall International Editions. 626pp.

Annex 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 $q_iF_{max.i} = bMR_i$.
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.
$ß_i$ = Expected penalty in category i.
X = Total number of vessel units that can be licensed.
c_i = Relative efficiency of vessels in category i.