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OPTIMAL MANAGEMENT OF A RENEWABLE RESOURCE IN A MULTISPECIES ECOSYSTEM

BY

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THESIS SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

THE CITY UNIVERSITY

DEPARTMENT OF SYSTEMS SCIENCE

NOVEMBER 1989

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ACKNOWLEDGEMENTS

I wish to express my greatest appreciation and gratitude to my research supervisor, Dr. F.J. Charlwood who has patiently guided and assisted me throughout my research. His valuable comments and suggestions have greatly eased the difficulties I encountered during my research.

My debt of gratitude also goes to my wife, [redacted] and my children, [redacted] and [redacted] whose unending love, patience and support have been a source of inspiration and carried me through many difficult times.

I also wish to thank the [redacted] for providing financial assistance in the form of 'study leave grant' which enabled me to embark on my research career.

DECLARATION

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ABSTRACT

A bioeconomic model comprising a biological and economic submodels was constructed to illustrate the harvesting of the interdependent self-renewable natural resource in a multispecies ecosystem. The biological submodel describes the population dynamics of a finite number of interdependent self-renewable resources while the economic submodel describes the economics and dynamics of the exploitation process. A harvest (production) function which is capable of accommodating any finite number of economic inputs links these two submodels.

Three biological interspecies relationships -- predator-prey, competitive and symbiotic -- were briefly analysed, followed by the formulation of a dynamic multispecies optimization model with the objective of maximizing the total present value subject to the population dynamics of the biological submodel. By applying the optimal control theory, the optimization problem was reduced to an initial-value problem involving a system of nonlinear first order ordinary differential equations.

Two measures of fishing effort -- the hours fishing and ton-hours fishing -- and nine main commercial fish species comprising of six demersal and three pelagic species from the North Sea commercial harvests were chosen to illustrate the model. Results obtained suggested that the ton-hours fishing is a less satisfactory measure of fishing effort than the popular hours fishing. No optimal policy was obtained for the model. However, a suboptimal policy generated by the model includes elimination of some species, harvesting some species at their bioeconomic equilibrium levels, harvesting some species at some economically profitable levels and periodic harvesting of some species.

Contrary to some results obtained by others for a single species model, the suboptimal approach paths obtained in this nonlinear multispecies model do not involve radical measures such as maximum harvesting and zero harvesting. The transitions from the initial levels to the long run suboptimal equilibrium levels follow a relatively 'smooth' approach paths with the possibility of 'overshooting' and/or 'undershooting' the suboptimal levels in the early periods.

Some fishery regulations and issues at national and international levels were also briefly examined.

CHAPTER 1

INTRODUCTION

1.1 Focus of Study

The focus of this study is on fishery as a renewable resource. The fishery biomass is viewed as 'biological capital' in the sense that it is capable of generating a stream of harvests over time. At the same time, provided it is not subjected to excessive exploitation, this capital resource is also capable of self-renewing. Thus a more appropriate term for the case of fishery is that of a biologically self-renewable natural resource. The basic defining characteristic adopted in the study for this resource is that its growth rate is a function of its own stock size. One of the main aims of any fishery manager (or authority) is therefore to regulate fishing so as to produce the largest possible harvest that can be sustained indefinitely by maintaining the stock size at some optimal or suboptimal level (however that may be defined).

Most fisheries are multispecies and are usually characterised by a large number of different types of fishing gears, each exploiting a number of the species. At the same time, many fish species interact with other fish species which are also being harvested. Thus changes in the stock size of one species not only affect its own stock size but also the stock sizes of

other interacting species. This gives rise to two important interdependencies, technological and biological which should be accounted for in determining the optimal or suboptimal exploitation of this self-renewable resource.

The usual single species biological population dynamic models are therefore only partially applicable when dealing with the exploitation of fish resource in a multispecies ecosystem. Many fisheries are composed of both competitive and symbiotic species, while some species also prey on other species. All these three cases, in addition to human predation are considered in the study.

1.2 Objectives of Study

The main aim of the study is to determine the optimal or suboptimal paths of exploitation in a multispecies ecosystem. The objective of optimization adopted is the maximization of present value, that is the total discounted net economic returns from fishery, subject to the constraints associated with the multispecies population dynamic models. Both the biological and technological interdependencies are accounted for in the models.

The biological interdependence is featured by the inclusion of the interspecific species interaction terms into the population dynamic model. The economic or technological interdependence on the other hand

focuses on the fact that a single 'fishing effort' is capable of harvesting more than one species and, at the same time, any one species is also subjected to exploitation by more than one fishing effort at any one time. This is reflected in the economic submodel by the introduction of a 'directed composite fishing effort'.

The objectives of the study can thus be summarised as :

1. extending the single species biological model to a dynamic multispecies self-renewable resource model applicable to multispecies fishery,
2. specification and estimation of the catch or harvest production functions for each species included in the model,
3. estimation of biological parameters and a system of constraints within the framework of the multispecies model,
4. identification of the price structure and estimation of a system of price demand equations for the species as well as the derivations of the total revenue and total cost functions,
5. the formulation of a dynamic multispecies optimization model and a multi-dimensional dynamic optimization technique, and
6. the applicability of the model by determining the optimal or suboptimal paths of the North Sea commercial fisheries and testing the sensitivity of these solutions to changes in discount rate,

unit price and unit cost of harvest.

The ambiguity surrounding the concept of fishing effort motivates us to experiment with two measures of fishing activity -- the most popular, hours fishing and the vessel-capacity-included, ton-hours fishing. The former measure is defined as the number of hours the vessels were in the water and fishing (ICES, various years) while the later is the product of the hours fishing and the vessel's average gross registered tonnage (GRT).

1.3 Scope and Limitations of Study

The scope of the study is restricted in some important aspects. The model developed constitutes only a partial view of the whole real system. The model focuses on the harvesting activity which bridges the biological and economic submodels. Uncertainties and fluctuations in the ecosystem were assumed to exhibit minimum influence on the biological submodel. These assumptions, however are less likely to be true, for example in temperate marine fisheries where environmental variability can affect, among others, the growth and the abundance of the stock. The economic submodel on the other hand is mainly characterised only by the price and cost functions. Other economic, social and political factors were assumed to remain homogeneous throughout the system.

With respect to model application, the scope

is confined to the North Sea commercial fishery. Despite the importance of the fishery in terms of commercial catches, severe data limitations constrained any detailed analysis of this sector. The data utilised in this study consist primarily of secondary data published annually by ICES and MAFF. Its highly aggregate nature has forced considerable simplifications in the building of the empirical models.

Although the North Sea fishery is one of the most commercially valued, it is almost impossible to include all the species harvested. The constraint met in gathering data on fishing effort limits the time period to only 1960-1975. No complete data on fishing effort was published in the Bulletin Statistique after that period. This could be largely due to the eviction of most of the fishing fleets (especially those of the eastern bloc) from the fishing ground following the adoption of 200-mile Exclusive Economic Zones (EEZs) in 1977 by the coastal countries.

The absence of data on costs of commercial fishing vessels operating in the North Sea forces us to adopt a less realistic linear cost function. This is estimated from the revenues per unit of fishing effort where revenues were based on the prices of fish landed in United Kingdom expressed in 1975 prices.

The poor data availability on fishing effort also imposes constraint on the economic production

model. Throughout the study, the catchability coefficient which is a measure of the vessel's fishing power is assumed unchanged over time.

Although the unit price of fish is normally assumed fixed in most fishery analysis, the study adopts a demand function with a finite price elasticity of demand. Under this assumption, the unit price of fish varies inversely with the harvest — a higher harvest will lower the unit price while a smaller harvest will increase the unit price. This seems to be closer to reality than the assumption of constant unit price.

Despite these limitations, it is hoped that the theoretical and empirical formulations presented in the study will prove useful to others engaged in the empirical analysis of the fisheries under similar data constraints.

1.4 Outline of Study

The chapter outline of the study is as follows. Chapter 1 which is the current chapter spells out the focus and objectives of the study as well as its scope and limitations.

Chapter 2 provides an introduction to the general theory of a bioeconomic modelling. The analysis in this chapter is confined to a single species environment. Biological aspects of growth and production are discussed, leading to the formulation of a

population dynamic and production (harvesting) functions. The economic side looks at revenue and cost as functions of the economic input, the fishing effort and the output, the harvest. The long run open-access bioeconomic equilibrium associated with the dissipation of economic rent is considered. The chapter ends with a review of the dynamic optimum, the maximization of present value, for both cases of constant and variable unit price of output.

Chapter 3 is devoted mainly to the construction of an empirical model of a dynamic multispecies fishery. The single species model of Chapter 2 is extended to a multispecies ecosystem model. Three cases of species interactions — competitive, predator-prey and symbiotic — are briefly discussed. The continuous multispecies model is transformed to a discrete multispecies model in order to simplify the task of estimating biological parameters. This is facilitated by introducing a new variable, the catch per unit of fishing effort (cpue). The two submodels (biological and economic) are utilised to produce a dynamic multispecies optimization model whose objective is the maximization of the present value.

In Chapter 4, a dynamic multi-dimensional optimization technique applicable to the optimization model developed in an earlier chapter is formulated. The sensitivities of a two-species model exhibiting the three types of species interactions together with an

independent case are analysed.

Chapter 5 summarises the bioeconomic parameters estimated for the North Sea fishery based on the two measures of fishing effort — hours fishing and ton-hours fishing. The suboptimal time paths for each species generated by the simulation of the optimization technique formulated in Chapter 4 are recorded in Chapter 6. In the same chapter, the sensitivity of the suboptimal stock and harvest levels to changes in the discount rate, the unit price and unit cost is also illustrated.

Matters concerning fishery regulations and issues at national and international levels are briefly discussed in Chapter 7.

Chapter 8 contains a summary of the study and all conclusions rendered. Also included are suggestions for further research.

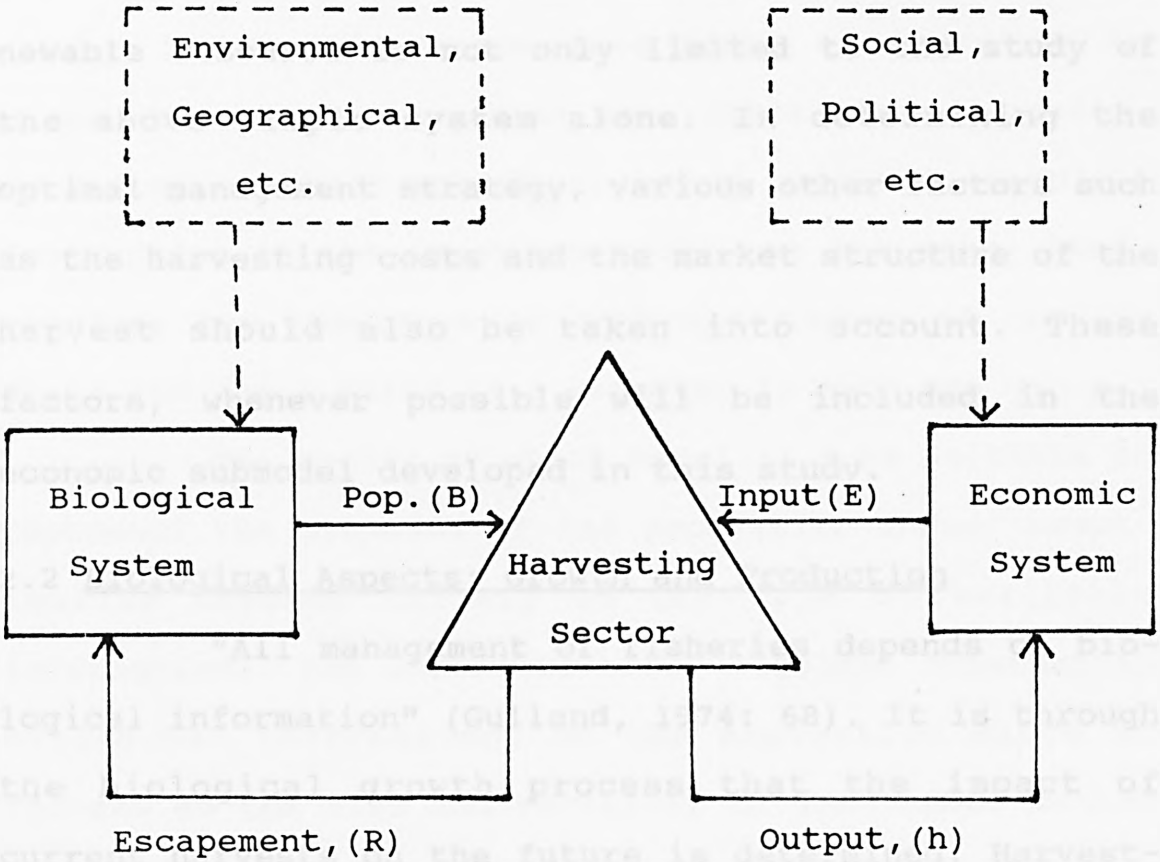
CHAPTER 2

A GENERAL BIOECONOMIC MODEL

2.1 Introduction

The study of renewable natural resources such as fisheries involves the interplay between two major dynamic systems — biological and economic — hence the term 'bioeconomics'. Other factors such as environmental, geographical and meteorological also affect the biological system while those associated with social and political have the effect of directing the course of economic system. However, informations on these factors are not easy to determine and normally require a separate study. Thus as in most studies on renewable resources, we will assume these factors to be approximately constant. This bioeconomic system in general can be summarised by a simple system diagram as in figure 2.1.

The dynamics of the biological system is normally represented by a single state variable B. This can be associated with the number of individuals in the system or the population biomass or any other biological parameters capable of reflecting the changes in the dynamics of the system. Utilisation of economic resources such as labour and capital provides an input E which is normally taken to represent the control variable in the economic system. The interaction between these two systems via a harvesting sector



Adapted from: Clark (1974)

Figure 2.1 A general bioeconomic system

results in an output, the harvest to the economic system which in turn affects the dynamics of the biological system. The higher the harvest, the lesser is the return (or the escapement) to the biological system, and vice versa.

However, an optimal management study of a renewable resource is not only limited to the study of the above simple system alone. In determining the optimal management strategy, various other factors such as the harvesting costs and the market structure of the harvest should also be taken into account. These factors, whenever possible will be included in the economic submodel developed in this study.

2.2 Biological Aspects: Growth and Production

"All management of fisheries depends on biological information" (Gulland, 1974: 68). It is through the biological growth process that the impact of current harvests on the future is determined. Harvesting more now reduces the current population stock and may result in a more difficult and hence costly future harvests. Alternatively, harvesting less now may allow future harvests to be obtained more cheaply.

Basically there are two very different ways of describing the biological growth process or the population dynamics — the analytic or dynamic-pool model developed by Beverton and Holt (1957) and the surplus production model associated with Schaefer

(1957). Each explains the dynamics of a single species stock. The Schaefer's model assumes the entire population can be treated as a single homogenous group, while the more complex model of Beverton and Holt assumes homogeneity within age-class but not for the population as a whole. Complete knowledge of the population in the homogenous mass model is described by either the total biomass or the number of individuals, depending on which aspect is being modelled. Complete description in the age-class model, on the other hand, requires the knowledge of both the number of individuals and their sizes (e.g weights) in each age group.

The choice of which model is more suitable to represent the dynamics of the population under investigation depends largely on the type of available informations. Age structure model requires substantial biological informations on the population since it focuses on the size and mortality of individual member as functions of age. The focus of a homogenous mass model, on the other hand, is on the total biomass or weight of the entire population and neglect the individual member. Thus the homogenous mass model is often more preferable in analysing, for example a commercial fishery where the only biologically oriented information available may be just a history of the harvest in weight. Since the data available for this study is limited and is more applicable to the homogenous mass model, the bioeconomic model developed in this study

will be based on this model.

2.2.1 Population Dynamics of a Single Species Stock

In the absence of human predation, the net rate of natural growth of a single species population such as fish is normally assumed to depend on the size of the current stock and a set of environmental conditions. If $B = B(t)$ is the size of the population stock at time t, its net rate of growth can be expressed as

$$dB/dt = f(\theta_1,\ldots,\theta_n, B) \qquad (2.1)$$

where θ_i $(i = 1,\ldots,n)$ is the i^{th} environmental factor.

The size of the stock, B(t) may be expressed in terms of the total number of individuals or its total biomass. When the size of the stock is small, the competition for food does not contribute a constraint to the growth since it is available in abundance relative to the population. But as the population grows, the natural growth rate as a whole slows down due to the severe competition for food and surrounding. The size of the stock thus converges to a limiting equilibrium size, beyond which the natural environment concerned cannot sustained any further growth of the population. This limiting equilibrium size of the stock is often referred to in population dynamics as the 'carrying capacity' or saturation level of the environment in question.

Assuming that the influence of all environmental factors can be aggregated into a single index B_k, the limiting equilibrium population level, then

$$B_k = B_k(\theta_1,\ldots,\theta_n). \qquad (2.2)$$

Studies on environmental variability (for example, May et al, 1978; Horwood and Shepherd, 1981; Horwood, 1983; Reed, 1981) suggested that environmental influences may enter the model via either its effects on the intrinsic growth rate ('density-independent noise') and/or through fluctuations in the carrying capacity ('density-dependent noise'), each exhibiting different dynamic implications on the stock size and yield. For exploited population, variability can also enter via the harvesting effort term as well as being subjected to non-environmental (for example, economic) factors such as discount rate, unit price and unit cost of harvest.

May et al (1978) analysed the way environmental variability affects the population size for various recruitment models by considering the characteristic return time which describes 'the rate at which the effects of small pertubations die away' (May et al, 1978: p221). This was further reviewed and summarised by Reed (1981). The population size and yield were generally found to exhibit greater fluctuations as harvesting effort increases, for a given level of randomness. The magnitude of this fluctuation depends

largely on the precise form on the recruitment function being considered. However, for most recruitment functions 'the absolute fluctuation in the population numbers decreases as the harvest rate increases' (Reed, 1981: p72).

In the case of density-dependent environmental noise where stochasticity enters via random fluctuations in the environmental carrying capacity, the analysis is slightly complicated and the effect could be opposite to that of density-independent case. The amplitude of population fluctuations could actually increase, rather than decrease since the population is better able to 'track' changes in the environmental fluctuations (May et al, 1978).

However, since the study assumes minimum environmental influences on the biological submodel and the analysis is further confined to a deterministic model, equation (2.2) does not seem unreasonable. Furthermore, in later part of the study, the limiting equilibrium population level, B_k will be assumed constant.

Equation (2.1) can then be expressed in a simpler form

$$dB/dt = f(B_k, B) \ . \qquad (2.3)$$

The growth rate function $f(B_k,B)$ is assumed to be continuous, concave and exhibiting the following properties :

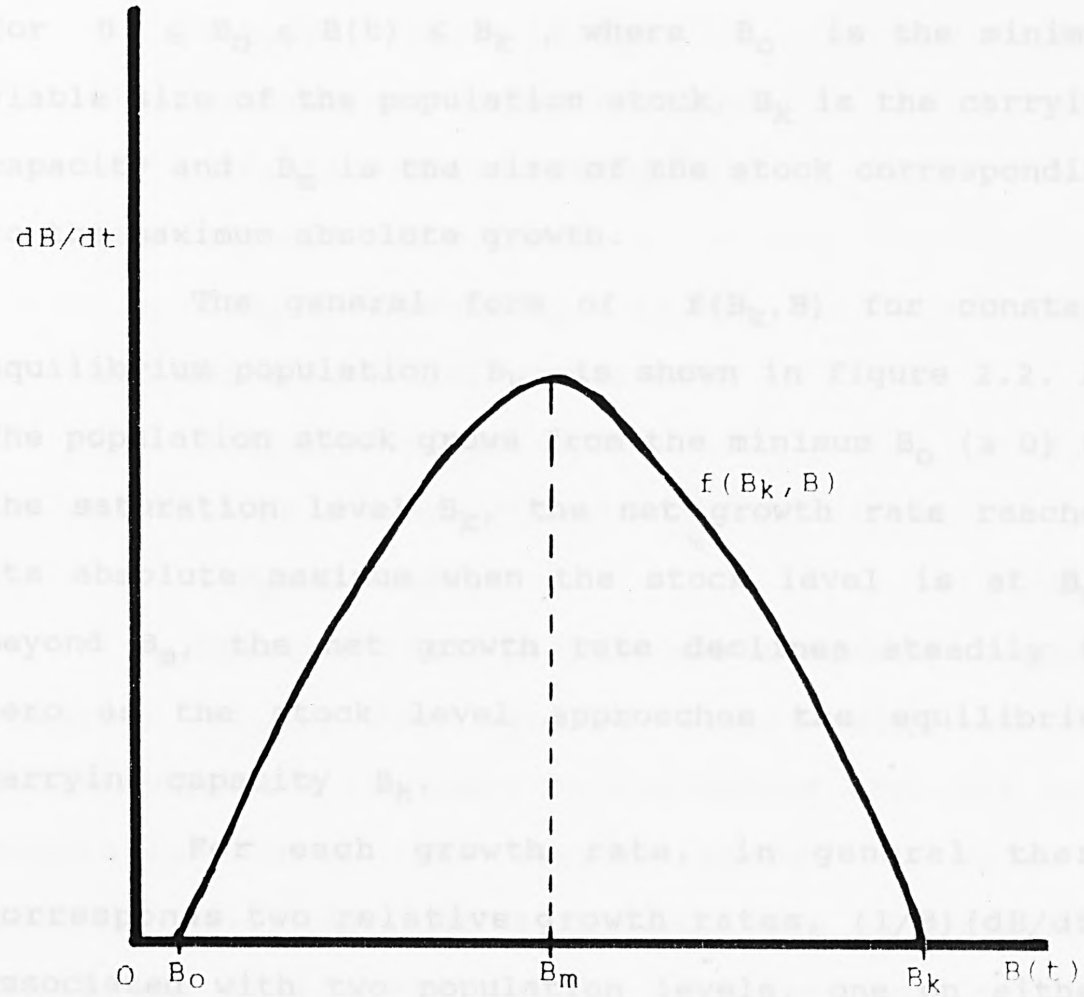


Figure 2.2 Graph of $f(B_k, B)$

(i) $f(B_k, B) \geq 0$,

(ii) $f(B_k, B_o) = f(B_k, B_k) = 0$,

(iii) $df(B_k,B)/dB = 0$ and $d^2f(B_k,B)/dB^2 < 0$ at $B = B_m$,

for $0 \leq B_o \leq B(t) \leq B_k$, where B_o is the minimum viable size of the population stock, B_k is the carrying capacity and B_m is the size of the stock corresponding to the maximum absolute growth.

The general form of $f(B_k,B)$ for constant equilibrium population B_k is shown in figure 2.2. As the population stock grows from the minimum B_o (≥ 0) to the saturation level B_k, the net growth rate reaches its absolute maximum when the stock level is at B_m. Beyond B_m, the net growth rate declines steadily to zero as the stock level approaches the equilibrium carrying capacity B_k.

For each growth rate, in general there corresponds two relative growth rates, $(1/B)(dB/dt)$ associated with two population levels, one on either side of B_m. The relative growth rate for a given net growth rate is greater when $B(t) < B_m$ than it is when $B(t) > B_m$, and single-value at $B(t) = B_m$. This positive relative growth rate is termed the 'per capita intrinsic growth rate' of the population.

During the past few decades, many single species models have evolved from equation (2.3), each adopting different form of growth function. Standard examples (Clark, 1975; Sancho and Mitchell, 1977)

include

the general logistic form

$$f(B_k,B) = aB - bB^2, \quad (2.4)$$

the Pearl-Verhulst or Schaefer's form

$$f(B_k,B) = rB(1 - B/B_k) , \quad (2.5)$$

the 'generalised' production model

$$f(B_k,B) = rB\{1 - (B/B_k)^{m-1}\}, \quad (2.6)$$

the Gompertz law

$$f(B_k,B) = rB(\ln B_k - \ln B), \quad (2.7)$$

and the exponential growth form

$$f(B_k,B) = r(B_k - B) \quad (2.8)$$

as well as a simpler form

$$f(B_k,B) = aB . \quad (2.9)$$

Observe that in the above models (except equation (2.8)) the minimum viable size of the population stock is taken to correspond with the zero population level. The surplus production form of equation (2.5) is just a special case of equations (2.4) and (2.6), and is the most popular version adopted in the homogenous mass model. Taking $m = 2$ reduces equation (2.6) to that of equation (2.5).

Solving

$$dB/dt = rB(1 - B/B_k) \quad (2.10)$$

for constant r and B_k yields

$$B(t) = B_k/(1 + Ae^{-rt}) \quad (2.11)$$

where

$$A = [B_k - B(0)]/B(0), \quad (2.12)$$

and $B(0)$ is the population stock at time $t = 0$.

The growth function (2.11) is known as the logistic growth function and the population growth path has the sigmoid (S) shape as shown in figure 2.3 (for $B(0) < B_k$). The relative growth rate as a function of the population size is a straight line (figure 2.4)

$$(1/B)(dB/dt) = r(1 - B/B_k). \qquad (2.13)$$

The maximum growth rate occurs at $B_m = (1/2)B_k$.

For the Gompertz growth curve, the maximum growth rate occurs at $B_m = B_k/e$. The relative growth rate is given by

$$(1/B)(dB/dt) = r(\ln B_k - \ln B) \qquad (2.14)$$

which is a curve convex to the origin and linear in ln B.

The exponential growth curve,

$$dB/dt = r(B_k - B) \qquad (2.15)$$

can be integrated to give

$$B(t) = B_k - [B_k - B(0)]e^{-rt} \qquad (2.16)$$

where B(0) is the initial population level at time t=0. Graphically, equation (2.16) generates population time path of the form shown in figure 2.5 for B(0) less than B_k. The relative growth rate, given by

$$(1/B)(dB/dt) = r(B_k/B - 1) \qquad (2.17)$$

is a hyperbolic curve with zero value at $B(t) = B_k$ and increases as the stock size decreases.

Of all the growth functions discussed above, the Schaefer's surplus production form exhibits all the required properties expected of $f(B_k,B)$ for a constant B_k. Although the exponential growth curve seems a close

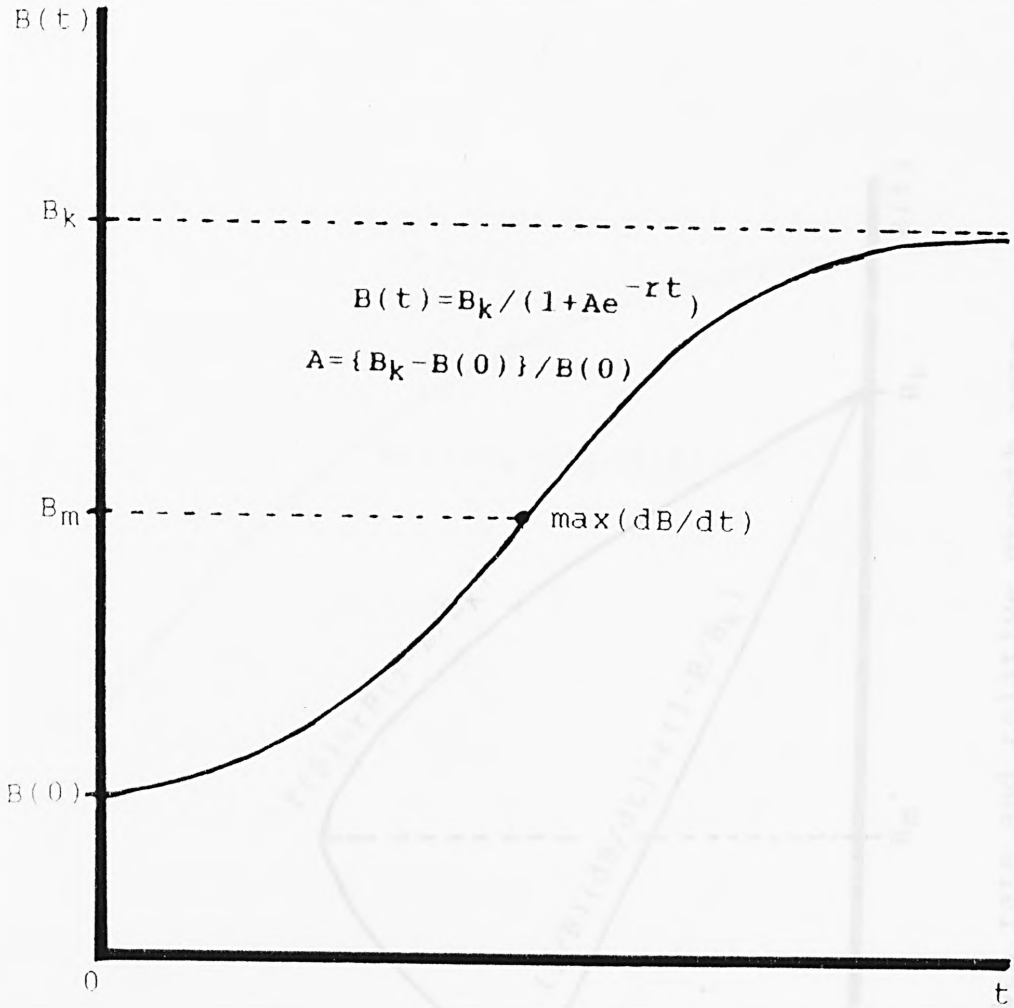


Figure 2.3 Logistic growth curve ($B(0)<B_k$)

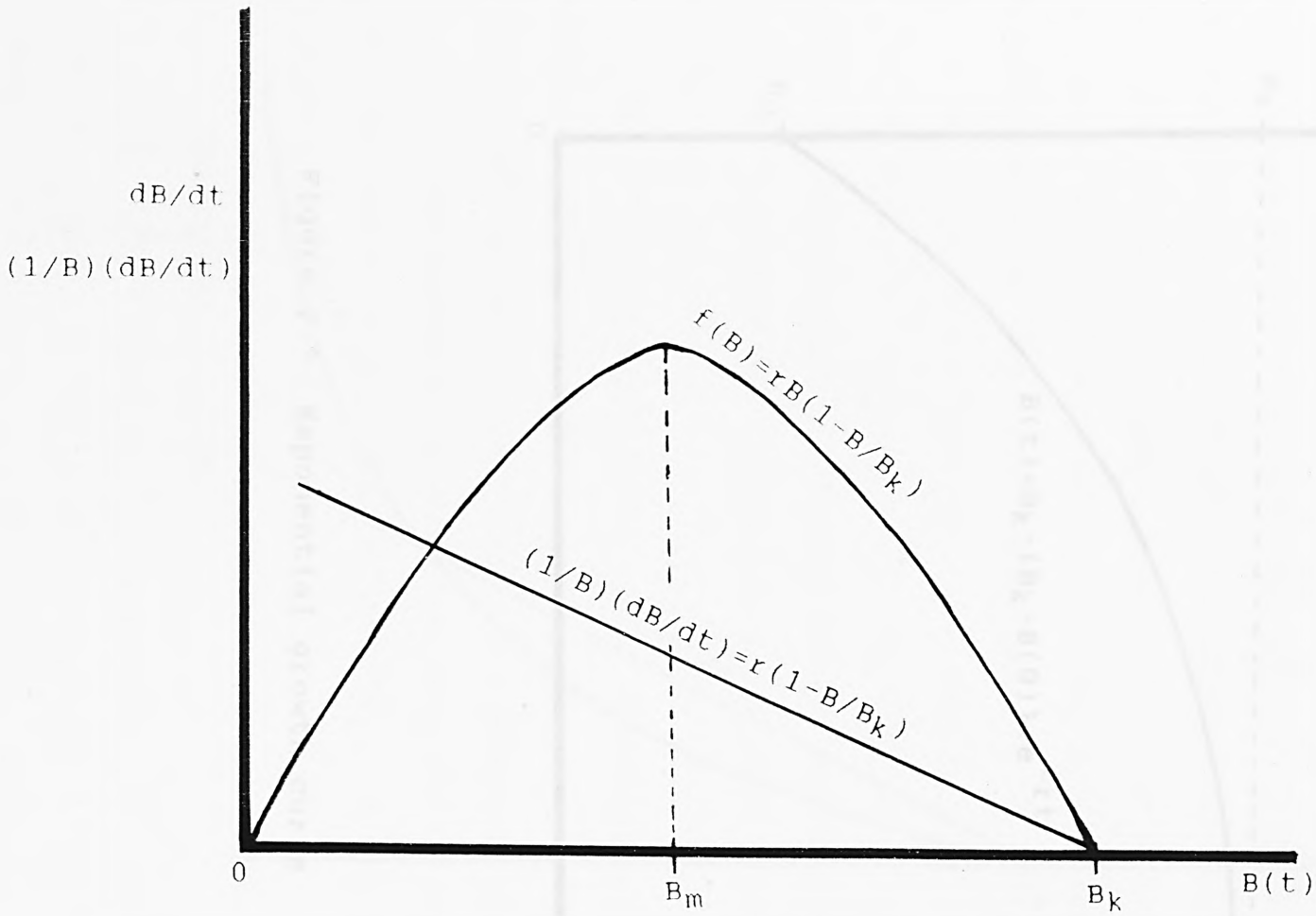


Figure 2.4 Growth rate and relative growth rate (logistic case)

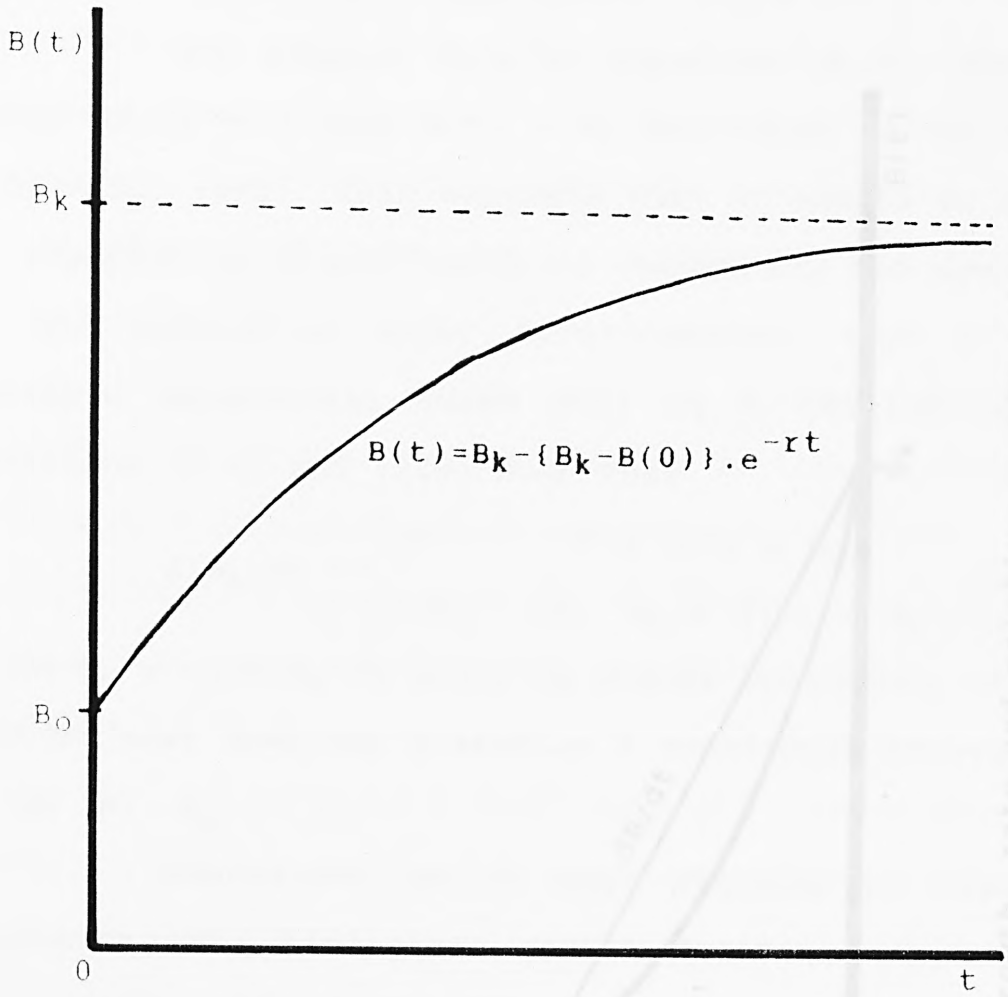


Figure 2.5 Exponential growth curve

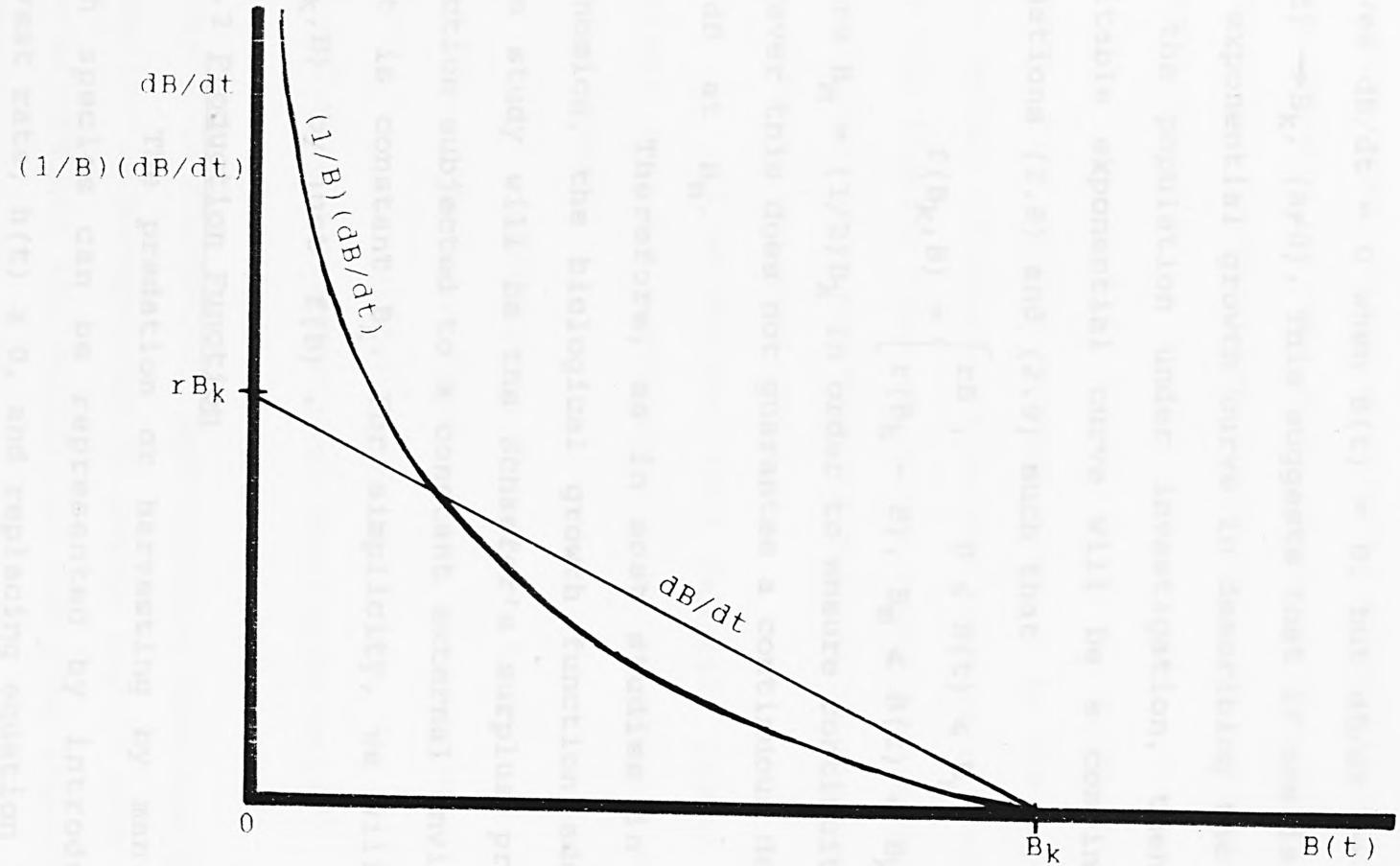


Figure 2.6 Growth rate and relative growth rate (exponential case)

approximation to the logistic curve, its growth rate function does not exhibit all the expected properties. From equation (2.15), it can be seen that as B(t) approaches zero, dB/dt approaches $rB_k \neq 0$.

The simpler form of equation (2.9), however gives dB/dt = 0 when B(t) = 0, but dB/dt $\rightarrow aB_k \neq 0$ as B(t) $\rightarrow B_k$, ($a \neq 0$). This suggests that if one is to adopt an exponential growth curve in describing the dynamics of the population under investigation, then a more suitable exponential curve will be a combination of equations (2.8) and (2.9) such that

$$f(B_k,B) = \begin{cases} rB, & 0 \leqslant B(t) \leqslant B_m \\ r(B_k - B), & B_m \leqslant B(t) \leqslant B_k \end{cases} \qquad (2.18)$$

where $B_m = (1/2)B_k$ in order to ensure continuity at B_m. However this does not guarantee a continuous derivative df/dB at B_m.

Therefore, as in most studies in fishery economics, the biological growth function adopted in this study will be the Schaefer's surplus production function subjected to a constant external environment, that is constant B_k. For simplicity, we will denote $f(B_k,B)$ by just f(B) .

2.2.2 Production Function

The predation or harvesting by man on the fish species can be represented by introducing a harvest rate, $h(t) \geqslant 0$, and replacing equation (2.3) by

$$dB/dt = f(B) - h(t). \qquad (2.19)$$

The size of catch or harvest which reflects the absolute depletion of the fish stock by fishing in a small unit of time in general depends on two main factors, the extend of fishing capacity — which include, among others, capital, labour, technology, fishing time, types of fishing gears and vessels — and the density of the fish stock in the fishing ground. Thus the production function, in general, can be represented by

$$h(t) = g(K, L, T, H, S, N) \qquad (2.20)$$

where h(t) is the harvest rate, K is the capital, L is the amount of labour, T is the measure of technology, H is the fishing time, S is the vessels's characteristics (including size and type of fishing gears) and N is the density of the fish stock.

If we assume that capital, labour and technology can be aggregated into a single efficiency index, then

$$\text{efficiency, } F = g_1(K, L, T) \qquad (2.21)$$

and the production function can be written

$$h(t) = g_2(F, H, S, N). \qquad (2.22)$$

By defining a standardised fishing effort(*)

$$E(t) = k\, g_3(F, H, S) \qquad (2.23)$$

where k is a constant, and assuming that the production function is homogeneous of degree one in both the fishing effort and the density of the fish stock enable us

---

(*) Fishing effort is discussed in section 3.3.1

to rewrite equation (2.22) as

$$h(t) = kE(t)N. \qquad (2.24)$$

Now, the density of the fish stock is related to the fishing ground by

$$N = B/A \qquad (2.25)$$

where $B = B(t)$ is the size (e.g biomass) of the fish stock and A is the size of the fishing ground.

If the exploitation is confined to a fixed fishing ground (e.g of constant area and approximately homogeneous depth), the production function becomes

$$h(t) = qE(t)B(t) \ , \qquad (2.26)$$

where q is a constant called the 'catchability coefficient'. Equation (2.26) expresses the harvest rate as a function of the fishing effort and the size of the fish stock,

$$h(t) = g(E(t), B(t)). \qquad (2.27)$$

As in the growth rate function, the production function is also expected to exhibit various properties, namely

(i) $\partial g/\partial E > 0$ and $\partial^2 g/\partial E^2 \leqslant 0$,

such that the fishery production is subjected to nonincreasing returns to fishing effort, and

(ii) $\partial g/\partial B > 0$ and $\partial^2 g/\partial B^2 \leqslant 0$,

such that the fishery production is also subjected to nonincreasing returns to the size of the fish stock.

Thus in a short run, for a fish stock of a given size, the addition of fishing effort increases the harvest, that is

$$g(E_2,B) > g(E_1,B) \qquad (2.28A)$$

for $E_2 > E_1$, and fixed B. Similarly, the larger is the size of the fish stock, the larger is the harvest from a given fishing effort, that is

$$g(E,B_1) > g(E,B_2) \qquad (2.28B)$$

for $B_1 > B_2$, and fixed E.

These family of short run production functions are depicted in figure 2.7 where they are superimposed with the natural growth rate curve. As the level of fishing effort increases from E_1 to E_2 to E_3, the harvest rate associated with a given level of fish stock such as B_3 also increases from h_{13} to h_{23} to h_{33}. Similarly, for a given level of fishing effort, say E_2, the harvest rate associated with increasing level of fish stock from B_3 to B_2 to B_1 increases from h_{23} to h_{22} to h_{21} respectively.

However, the harvest of a renewable resource such as fish in a given period affects the conditions of the future harvesting. The size of the fish stock is bound to change unless the harvest rate exactly matches the natural growth rate. As can be seen from equations (2.19) and (2.27)

$$dB/dt = 0 \quad \text{if} \quad f(B) = g(E,B). \qquad (2.29)$$

Consider a fishing effort of the amount E_2 (see figure 2.7). Suppose it is applied at a time when the fish stock is at level B_1, thus yielding a harvest $h_{21} = g(E_2,B_1)$. The absolute natural growth rate at

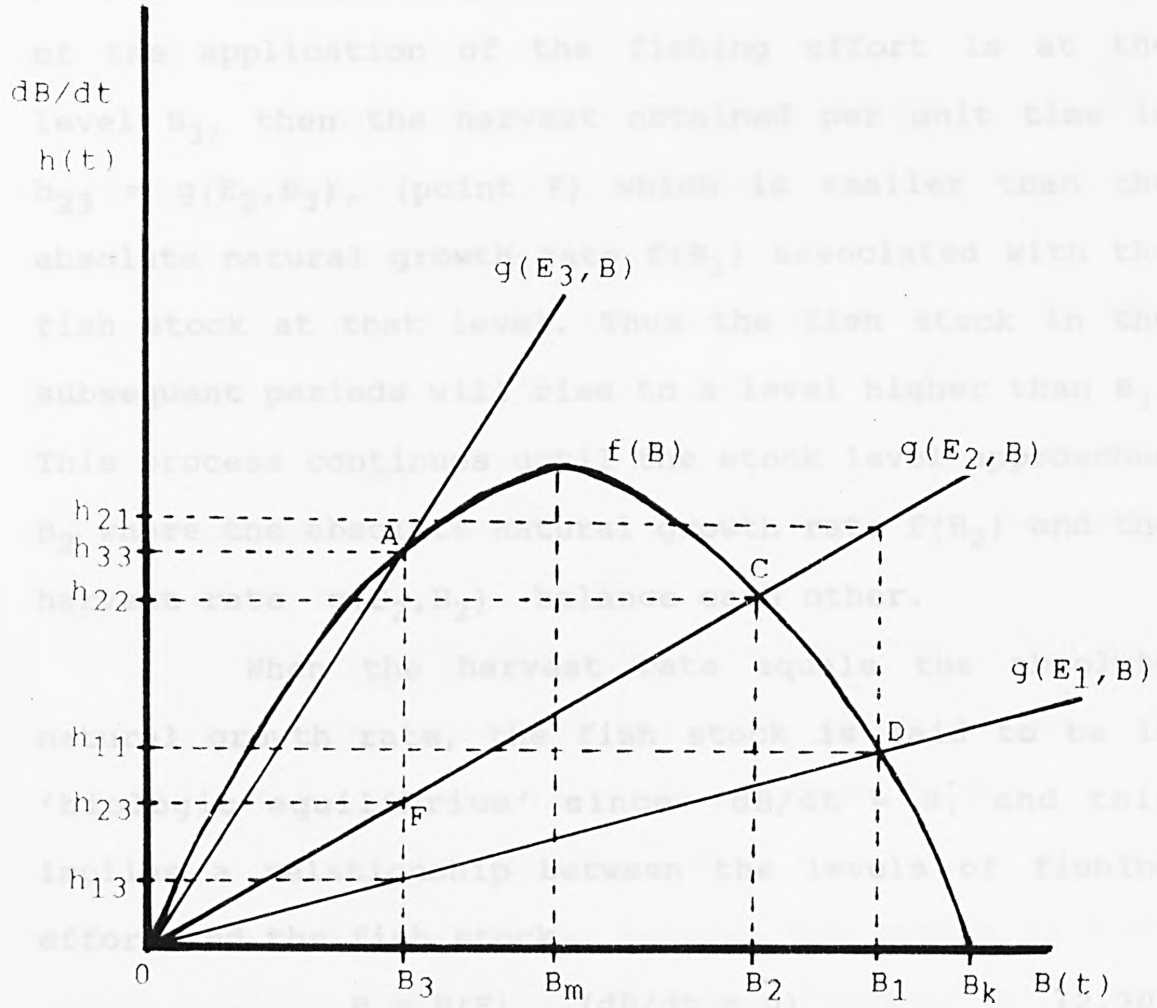


Figure 2.7 Short run production functions

this stock level is $f(B_1)$, (point D on the growth rate curve) and is smaller than $g(E_2,B_1)$. Thus the fish stock will fall to a lower level in the subsequent periods. Alternatively, if the fish stock at the time of the application of the fishing effort is at the level B_3, then the harvest obtained per unit time is $h_{23} = g(E_2,B_3)$, (point F) which is smaller than the absolute natural growth rate $f(B_3)$ associated with the fish stock at that level. Thus the fish stock in the subsequent periods will rise to a level higher than B_3. This process continues until the stock level approaches B_2 where the absolute natural growth rate $f(B_2)$ and the harvest rate $g(E_2,B_2)$ balance each other.

When the harvest rate equals the absolute natural growth rate, the fish stock is said to be in 'biologic equilibrium' since $dB/dt = 0$, and this implies a relationship between the levels of fishing effort and the fish stock,

$$B = B(E) \ , \ (dB/dt = 0) \qquad (2.30)$$

which upon substitution into the harvest function gives the sustainable catch-effort relationship,

$$h(t) = g(E,B(E)) = G(E). \qquad (2.31)$$

Solving equation (2.30) for the Schaefer's model gives

$$rB(1 - B/B_k) - qEB = 0 \ ,$$

which simplifies to

$$B = B_k - (qB_k/r)E \ , \ (B \neq 0). \qquad (2.32)$$

This gives

$$dB/dE = -(q/r)B_k \qquad (2.33)$$

which is constant and negative.

The sustainable catch-effort curve of (2.31) can then be written as

$$h(t) = qB_kE(t)\{1 - (q/r)E(t)\} \qquad (2.34)$$

which is quadratic in E(t). Differentiating equation (2.34) with respect to E(t) gives

$$dh/dE = qB_k\{1 - (2q/r)E(t)\} . \qquad (2.35)$$

For maximum harvest, dh/dE = 0. Thus

$$E_{msy} = r/(2q) , \qquad (2.36)$$

and the maximum sustainable yield (msy) or harvest, h_{msy} is given by

$$h_{msy} = (1/4)\ rB_k. \qquad (2.37)$$

The corresponding level of the fish stock capable of generating this harvest is, from equation (2.32)

$$B_{msy} = (1/2)B_k = B_m. \qquad (2.38)$$

These sustainable relations between the levels of fish stock, fishing effort and harvest, together with the natural growth rate curve are shown graphically in figure 2.8.

For a low level of fishing effort at E_1, the fish stock is virtually unexploited and is therefore relatively high at B_1. The natural growth rate and the equivalent sustainable yield is relatively low at level h_1. This corresponds to point $A(E_1,h_1)$ on the sustainable yield curve. Increases in fishing effort reduce the fish stock and the natural growth rate first

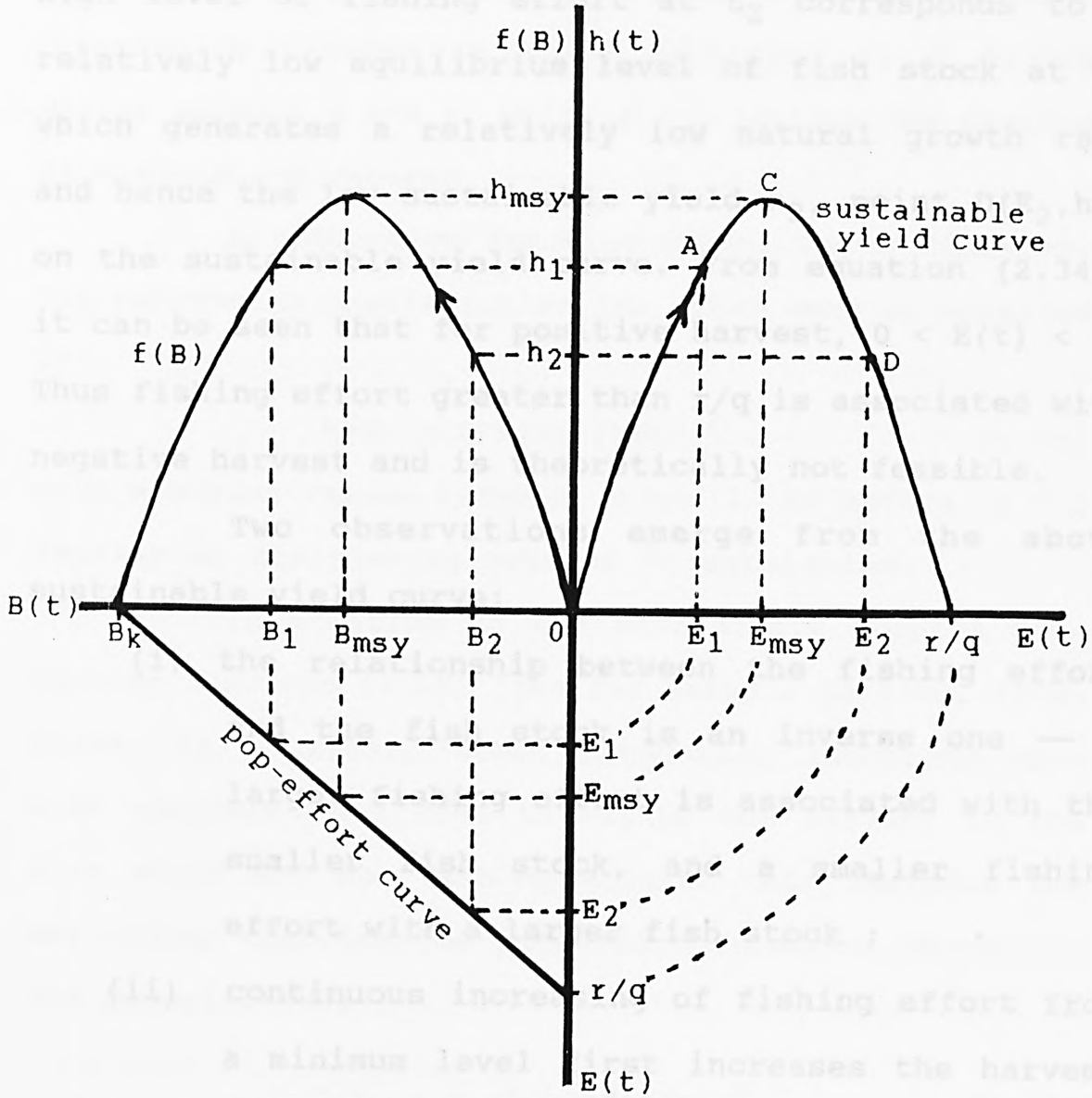


Figure 2.8 Relations between population-yield-effort and natural growth rate

rises and then falls. This induces a similar path for the sustainable yield, rising to a maximum at point $C(E_{msy},h_{msy})$ and then falling to zero. Similarly, a high level of fishing effort at E_2 corresponds to a relatively low equilibrium level of fish stock at B_2 which generates a relatively low natural growth rate and hence the low sustainable yield h_2, point $D(E_2,h_2)$ on the sustainable yield curve. From equation (2.34), it can be seen that for positive harvest, $0 < E(t) < r/q$. Thus fishing effort greater than r/q is associated with negative harvest and is theoretically not feasible.

Two observations emerge from the above sustainable yield curve:

(i) the relationship between the fishing effort and the fish stock is an inverse one — a larger fishing effort is associated with the smaller fish stock, and a smaller fishing effort with a larger fish stock ;

(ii) continuous increasing of fishing effort from a minimum level first increases the harvest to a maximum, after which it then declines even with further additions of fishing effort.

In the above analysis the production function is assumed to exhibit constant returns to both fishing effort and population. A production function exhibiting diminishing returns to fishing effort and population is studied by Anderson (1977) and Cunningham, Dunn and

Whitmarsh (1985). The short-run production function is modified to

$$h(t) = q \{E(t)\}^d B(t) \qquad (2.39)$$

where d represents variable returns to fishing effort. Diminishing returns is being signified by d having values between 0 and 1, while d = 1 implies the absence of diminishing returns.

A production function exhibiting a diminishing returns to population on the other hand is modelled by

$$h(t) = q E(t) \{B(t)\}^b . \qquad (2.40)$$

with b having values between 0 and 1. As before, b = 1 implies no diminishing returns to population.

In addition to the extensively adopted production function (2.26) (see for example Gulland, 1969; Clark, 1976, 1985), other production functions have been suggested and used to relate the harvest to the fish stock and the fishing effort. This includes the well-known Cobb-Douglas production function (Henderson and Tugwell, 1984),

$$h(t) = q \{E(t)\}^a \{B(t)\}^b, \qquad (2.41)$$

the constant elasticity of substitution production function,

$$h(t) = [q_1 \{E(t)\}^{-a} + q_2 \{B(t)\}^{-a}]^{-1/a} \qquad (2.42)$$

as well as the exponential production function of the form

$$h(t) = q \{1 - e^{-bE(t)}\} \{B(t)\}^a \qquad (2.43)$$

which is usually associated with discrete model (Spence, 1984).

For a = b = 1, the Cobb-Douglas production function reduces to the form of (2.26),

$$h(t) = q\, E(t) B(t) \ .$$

2.3 Economic Aspects : Revenue and Cost

Revenue and cost constitute central issues in the study of economic aspects of fishery exploitation. There are two common approaches to this analysis. The first is to relate revenue and cost to the economic input, the fishing effort and the second is the derivation of revenue and cost in terms of the output, the harvest.

2.3.1 Revenue as function of fishing effort (constant price)

The total revenue from fishing is just the harvest or yield translated into 'value terms'. If the price of fish is assumed constant, the total revenue generated is then given by

$$TR = p\, h(t) \qquad (2.44)$$

where p is the constant(*) price per unit of fish and h(t) is the total harvest at time t.

(*) This assumption is generally valid if the fishery under investigation constitutes only a small part of the total market supply for fish (Anderson, 1977; Cunningham et al, 1985).

Substituting equation (2.34) into equation (2.44), we get (dropping the variable t for simplicity)

$$TR = pqB_kE(1 - (q/r)E) \quad . \qquad (2.45)$$

This gives the total revenue as a function of the fishing effort. This sustainable revenue-effort curve is proportional to the sustainable yield curve derived earlier (figure 2.8). The exact shape will depend on the constant price p. A relatively high price will increase the peak of the curve while a lower price will have the effect of lowering it.

The average revenue, AR_E and the marginal revenue, MR_E with respect to the input E can be respectively derived by dividing and differentiating the total revenue, TR by and with respect to the fishing effort E. Thus

$$AR_E = (TR)/E = pqB_k(1 - (q/r)E) \qquad (2.46)$$

and

$$MR_E = d(TR)/dE = pqB_k(1 - (2q/r)E). \qquad (2.47)$$

The effect of variations in price on these revenues are depicted in figure 2.9 where $p_2 < p < p_1$ and TR_i, AR_i and MR_i are the total, average and marginal revenues associated with price p_i $(i = 1,2)$.

The average revenue curve AR_E which is a measure of revenue per unit of fishing effort at each level of fishing effort is negatively sloped since average catch per unit of fishing effort decreases as fishing becomes more intensified. Similarly, the marginal revenue curve, MR_E which measures the change

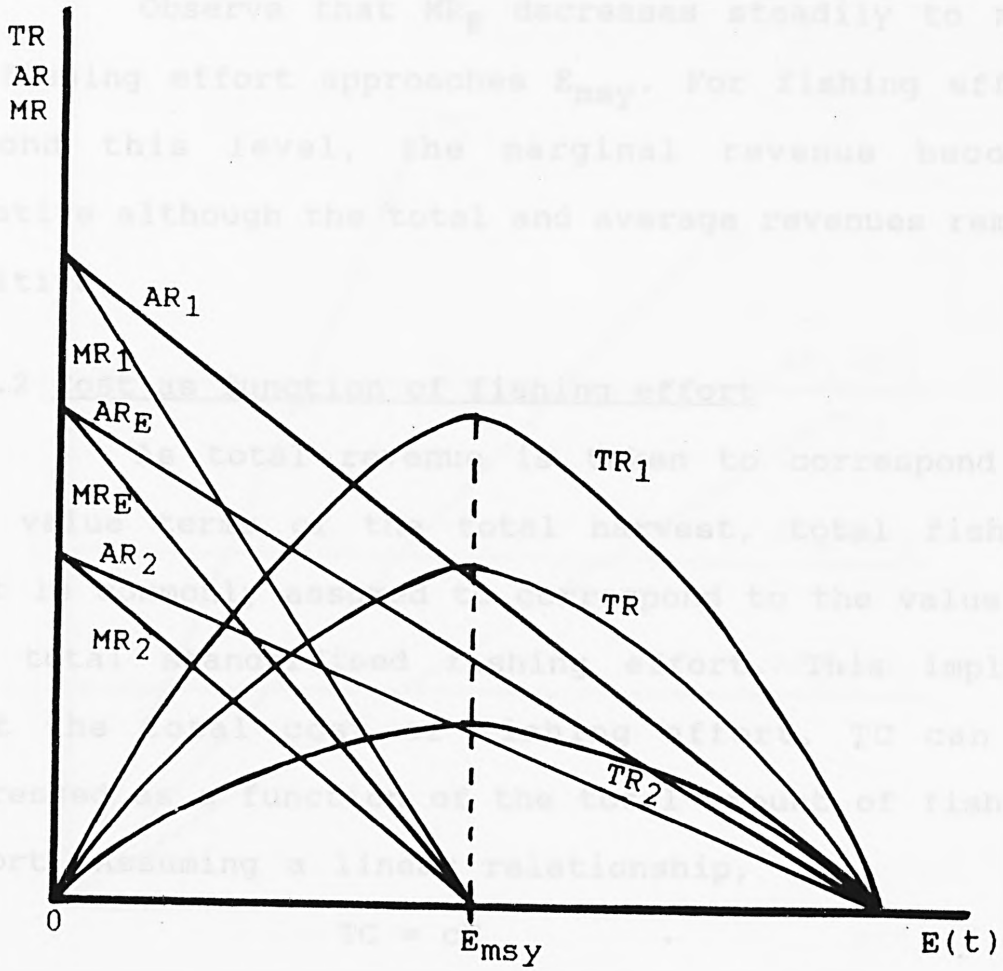


Figure 2.9 Revenue as function of fishing effort

in revenue resulting from a change in a unit of fishing effort is also negatively sloped (but twice as steep as the AR_E curve) because marginal catch per unit of fishing effort also declines under the same condition.

Observe that MR_E decreases steadily to zero as fishing effort approaches E_{msy}. For fishing effort beyond this level, the marginal revenue becomes negative although the total and average revenues remain positive.

2.3.2 Cost as function of fishing effort

As total revenue is taken to correspond to the value terms of the total harvest, total fishing cost is commonly assumed to correspond to the value of the total standardised fishing effort. This implies that the total cost of fishing effort, TC can be expressed as a function of the total amount of fishing effort. Assuming a linear relationship,

$$TC = cE \qquad (2.48)$$

where c is a constant cost per unit of fishing effort. The average cost, AC_E and the marginal cost, MC_E with respect to fishing effort are given by

$$AC_E = (TC)/E = c \quad \text{and} \quad MC_E = d(TC)/dE = c \ .$$

Thus, we have

$$AC_E = MC_E = c \ . \qquad (2.49)$$

Variations in c will induce linear changes in TC, AC_E and MC_E as depicted in figure 2.10 where

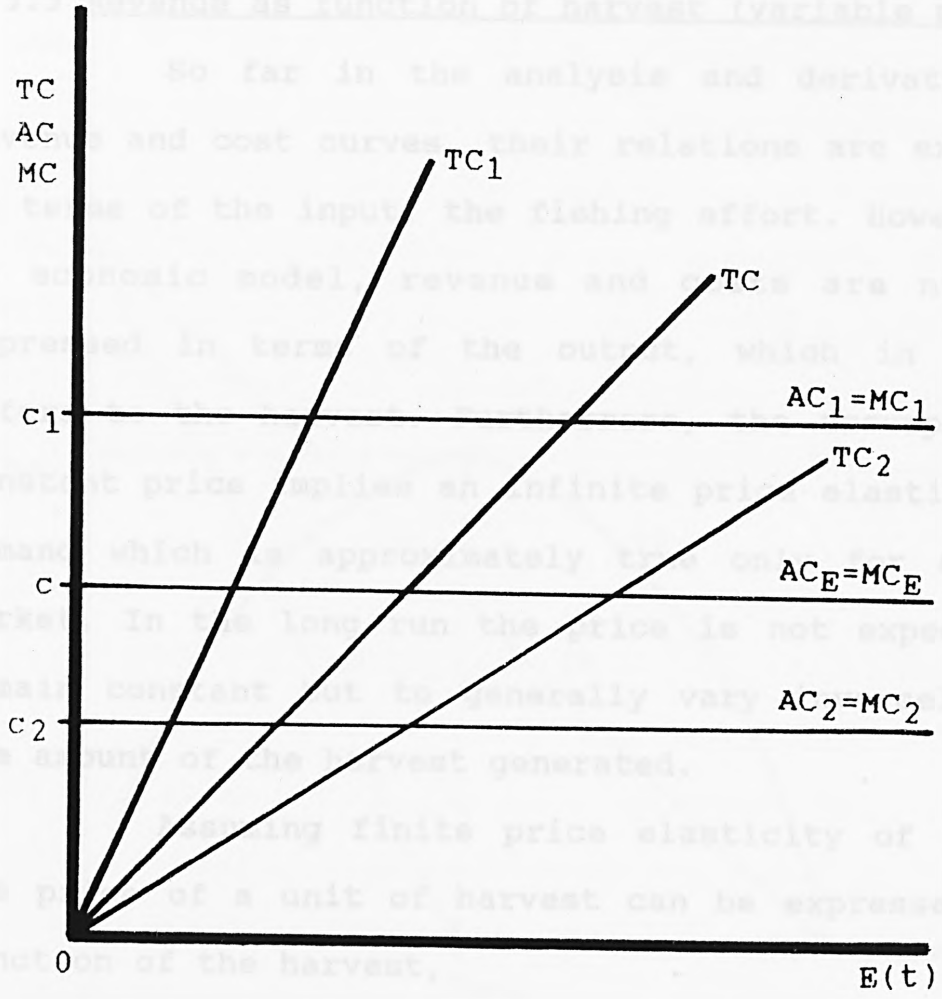


Figure 2.10 Cost as function of fishing effort

$c_2 < c < c_1$ and TC_i, AC_i and MC_i are the total, average and marginal cost curves associated with the unit cost c_i $(i = 1,2)$.

2.3.3 Revenue as function of harvest (variable price)

So far in the analysis and derivations of revenue and cost curves, their relations are expressed in terms of the input, the fishing effort. However, in an economic model, revenue and costs are normally expressed in terms of the output, which in fishery refers to the harvest. Furthermore, the assumption of constant price implies an infinite price elasticity of demand which is approximately true only for a small market. In the long run the price is not expected to remain constant but to generally vary inversely with the amount of the harvest generated.

Assuming finite price elasticity of demand, the price of a unit of harvest can be expressed as a function of the harvest,

$$P(h) = p_o - bh \qquad (2.50)$$

where p_o and b are positive constants. The constant p_o represents the maximum price that the society is prepared to pay for a unit of harvest.

The total revenue generated in the fishery is then given by

$$\begin{aligned} TR &= P(h).h \\ &= (p_o - bh)h \end{aligned} \qquad (2.51)$$

which is quadratic in harvest.

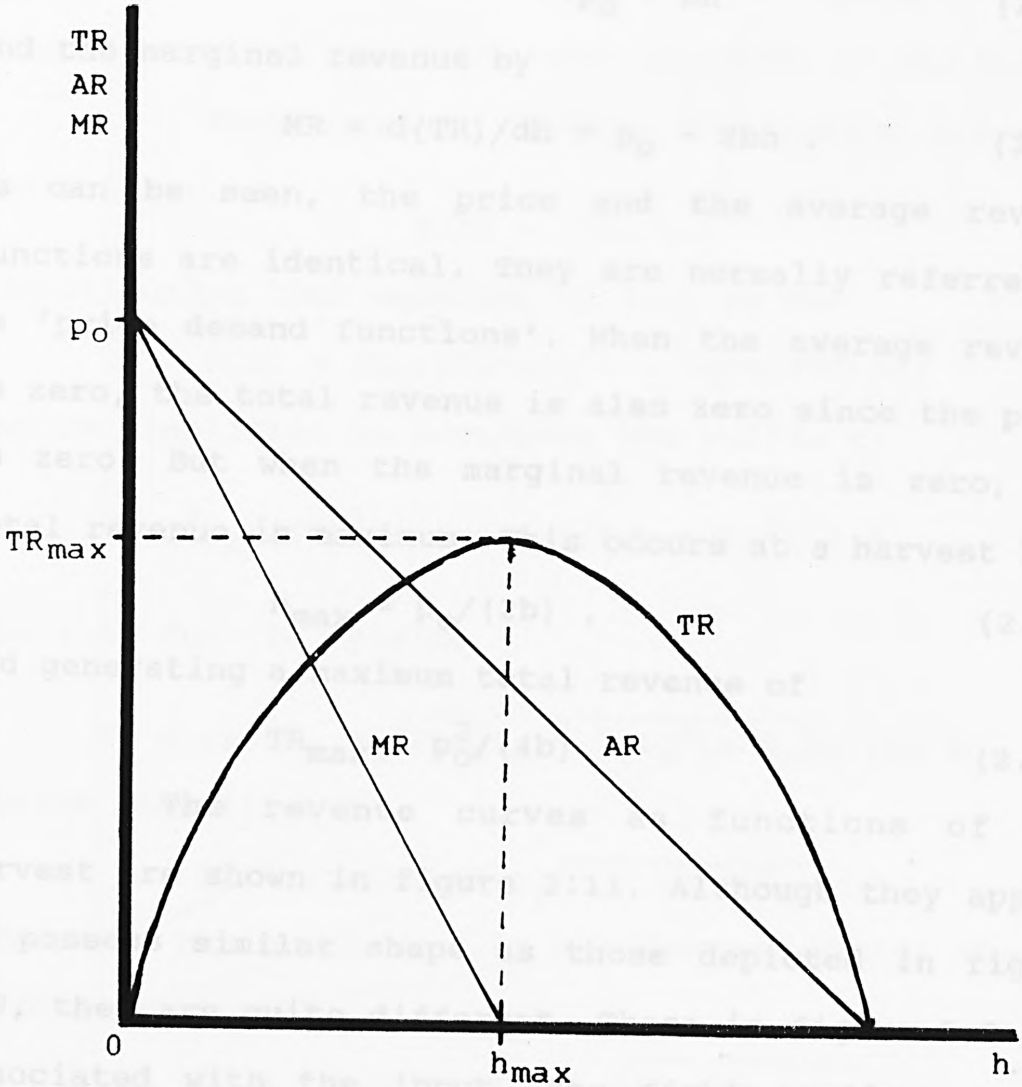


Figure 2.11 Revenue as function of harvest

(variable price)

The average revenue is given by

$$AR = (TR)/h = P(h)$$

$$= p_o - bh \qquad (2.52)$$

and the marginal revenue by

$$MR = d(TR)/dh = p_o - 2bh \ . \qquad (2.53)$$

As can be seen, the price and the average revenue functions are identical. They are normally referred to as 'price demand functions'. When the average revenue is zero, the total revenue is also zero since the price is zero. But when the marginal revenue is zero, the total revenue is maximum. This occurs at a harvest level

$$h_{max} = p_o/(2b) \ , \qquad (2.54)$$

and generating a maximum total revenue of

$$TR_{max} = p_o^2/(4b) . \qquad (2.55)$$

The revenue curves as functions of the harvest are shown in figure 2.11. Although they appear to possess similar shape as those depicted in figure 2.9, they are quite different. Those in figure 2.9 are associated with the input, the fishing effort and a constant unit price of harvest. The revenue curves (TR, AR and MR) in figure 2.11, on the other hand, are associated with the output, the harvest, and a variable unit price.

2.3.4 Cost as function of harvest

The derivation of the long run total cost as a function of the harvest requires the transformation of the fishing effort into the harvest. This can

mathematically be achieved by eliminating the fishing effort between the total cost function (2.48) and the sustainable catch-effort relation of equation (2.34), and solving for the total cost in terms of the harvest.

From equation (2.48), the fishing effort can be written as

$$E(t) = (TC)/c.$$

Substituting into equation (2.34), we get

$$h(t) = qB_k[(TC)/c][1 - (q/r)(TC)/c]$$

which simplifies to (dropping the suffix t)

$$(q^2B_k)(TC)^2 - (rcqB_k)(TC) + rc^2h = 0. \qquad (2.56)$$

Solving for TC yields

$$TC = \{rcqB_k \pm \sqrt{(rcqB_k)^2 - 4q^2rc^2B_kh}\}/(2q^2B_k)$$

which simplifies to

$$TC = (cr/2q)\{1 \pm \sqrt{1 - 4h/(rB_k)}\}. \qquad (2.57)$$

Dividing the total cost by the harvest yields the long run average cost

$$AC = [cr/(2qh)]\{1 \pm \sqrt{1 - 4h/(rB_k)}\} \qquad (2.58)$$

while differentiating it with respect to harvest yields the long run marginal cost

$$MC = [c/(qB_k)]/\sqrt{1 - 4h/(rB_k)}\ . \qquad (2.59)$$

The graph of the cost curves as functions of harvest are depicted in figure 2.12. As harvest increases to the maximum sustainable yield, h_{msy} the total cost increases at an increasing rate. Although further harvesting beyond this level causes the harvest to fall (due to decreasing population level in response

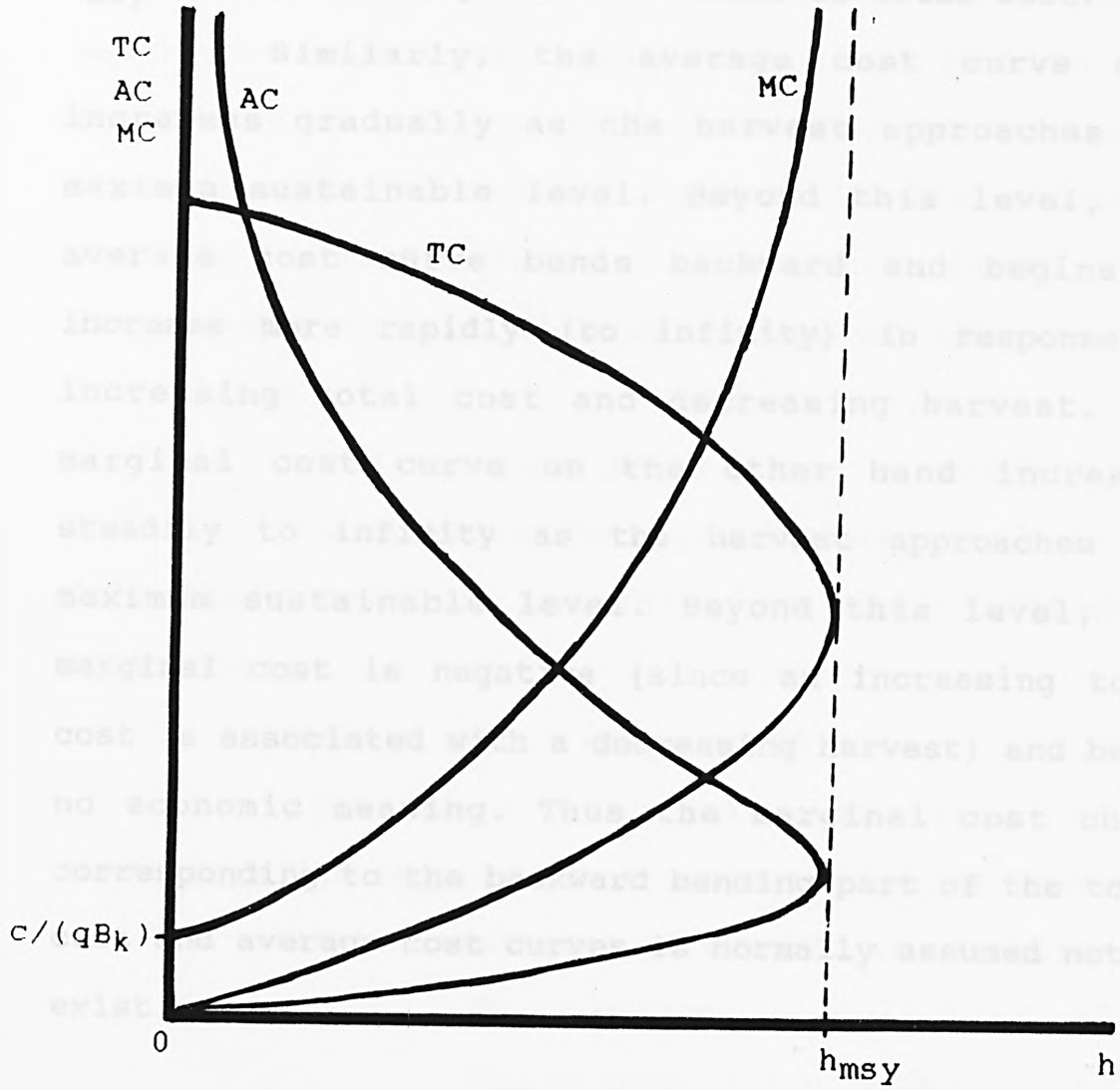


Figure 2.12 Cost as function of harvest

to increasing fishing effort), the total cost continues to rise. Thus for any given level of harvest (except at h_{msy}), there corresponds two values of total cost.

Similarly, the average cost curve also increases gradually as the harvest approaches the maximum sustainable level. Beyond this level, the average cost curve bends backward and begins to increase more rapidly (to infinity) in response to increasing total cost and decreasing harvest. The marginal cost curve on the other hand increases steadily to infinity as the harvest approaches the maximum sustainable level. Beyond this level, the marginal cost is negative (since an increasing total cost is associated with a decreasing harvest) and bears no economic meaning. Thus the marginal cost curve corresponding to the backward bending part of the total cost and average cost curves is normally assumed not to exist.

2.4 The Open-Access Fishery : Bioeconomic Equilibrium

Since the resource base of fishing is renewable, fishing as an economic activity should be capable of generating a stream of economic benefits which if properly managed could be sustained indefinitely. It has been argued (see for example Anderson, 1977; Clark, 1976; Cunningham et al, 1985) that a fishery resource which is subjected to a 'completely unregulated open-access' exploitation will reach a long run equilibrium

state called the 'bioeconomic equilibrium' (or sometimes known as bionomic equilibrium). This equilibrium is characterised by simultaneous economic and biologic equilibria — economic equilibrium since at this point the profit or economic rent is completely dissipated; biologic equilibrium since the relationship can now be sustained indefinitely at the stock level which corresponds to the fishing effort of the economic equilibrium .

For a constant price p and a constant unit cost c, this bioeconomic equilibrium level in the Schaefer's model is determined by the simultaneous equations

$$dB/dt = rB(1 - B/B_k) - qEB = 0 \qquad (2.60)$$

$$Z = (TR) - (TC) = pqEB - cE = 0 \qquad (2.61)$$

where Z is the economic rent generated in the fishery.

Solving equations (2.60) and (2.61) gives

$$B_{\infty} = c/(pq) \qquad (2.62)$$

$$E_{\infty} = (r/q)(1 - c/(pqB_k)), \qquad (2.63)$$

where B_{∞} and E_{∞} are the fish stock and fishing effort levels associated with the bioeconomic equilibrium.

Figure 2.13 shows the long run bioeconomic equilibrium level A corresponding to the fishing effort E_{∞}. It is represented by the intersection between the total revenue curve TR and the total cost curve TC. The fishing effort increases as long as average profit remains positive even if the marginal profit becomes negative (beyond point D in figure 2.13(b)), since not

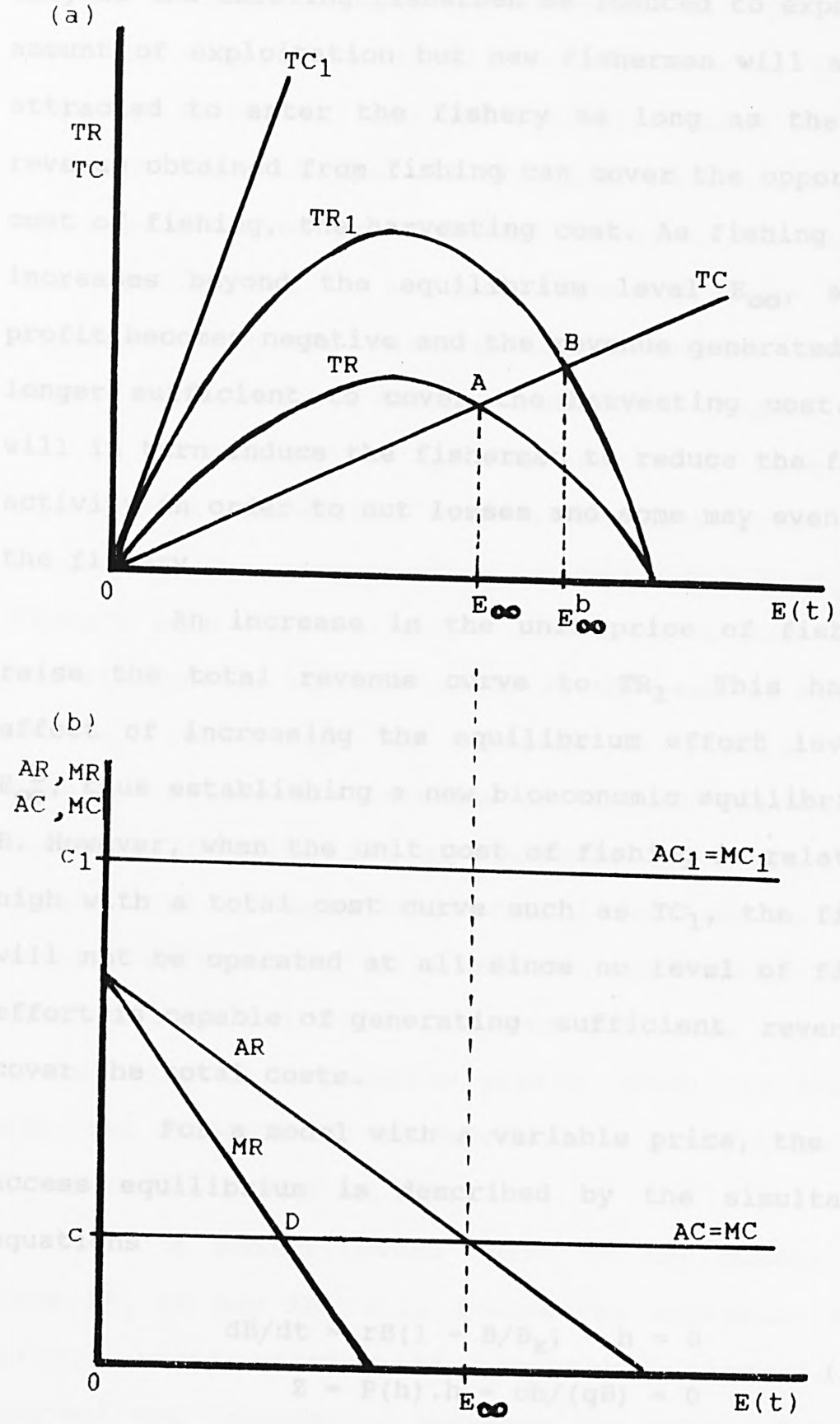


Figure 2.13 Open-access equilibrium

only is the existing fishermen be induced to expand the amount of exploitation but new fishermen will also be attracted to enter the fishery as long as the total revenue obtained from fishing can cover the opportunity cost of fishing, the harvesting cost. As fishing effort increases beyond the equilibrium level E_{∞}, average profit becomes negative and the revenue generated is no longer sufficient to cover the harvesting cost. This will in turn induce the fishermen to reduce the fishing activity in order to cut losses and some may even leave the fishery.

An increase in the unit price of fish will raise the total revenue curve to TR_1. This has the effect of increasing the equilibrium effort level to E_{∞}^{b}, thus establishing a new bioeconomic equilibrium at B. However, when the unit cost of fishing is relatively high with a total cost curve such as TC_1, the fishery will not be operated at all since no level of fishing effort is capable of generating sufficient revenue to cover the total costs.

For a model with a variable price, the open-access equilibrium is described by the simultaneous equations

$$\begin{aligned} dB/dt &= rB(1 - B/B_k) - h = 0 \\ Z &= P(h).h - ch/(qB) = 0 \end{aligned} \tag{2.64}$$

where $P(h) = p_o - bh$.

At the bioeconomic equilibrium level, all the economic rent is completely dissipated (following the same argument as before) and the average revenue equals the average cost. Since the average revenue curve is synonymous to the price demand function, the bioeconomic equilibrium in an open-access fishery is thus represented by the intersection(s) between the price demand curve and the average cost curve (figure 2.14).

The point A_o represents a bioeconomic equilibrium associated with a constant price demand curve AR_o. The corresponding harvest level is h_{∞}^{o}. For fishery with variable price demand curve such as AR_1, the bioeconomic equilibrium is established at A_1 with a harvest level h_{∞}^{1}. An increase in fishing effort results in long run increase in harvest followed by a decrease in price and an increase in average cost, giving rise to negative profit. A decrease in fishing effort, on the other hand, reduces the harvest and the average cost and which in turn increases the price, giving rise to a positive profit. Thus, in the long run, the fishery will be driven to an equilibrium level A_1 where the profit is zero.

A sudden upward shift in the demand curve from AR_1 to say AR_3 will induce the expansion in the effort level which will temporarily increase the harvest and temporarily decrease the price. The level of the fish stock is reduced and the fishery will eventually settle at the new equilibrium level A_3 which

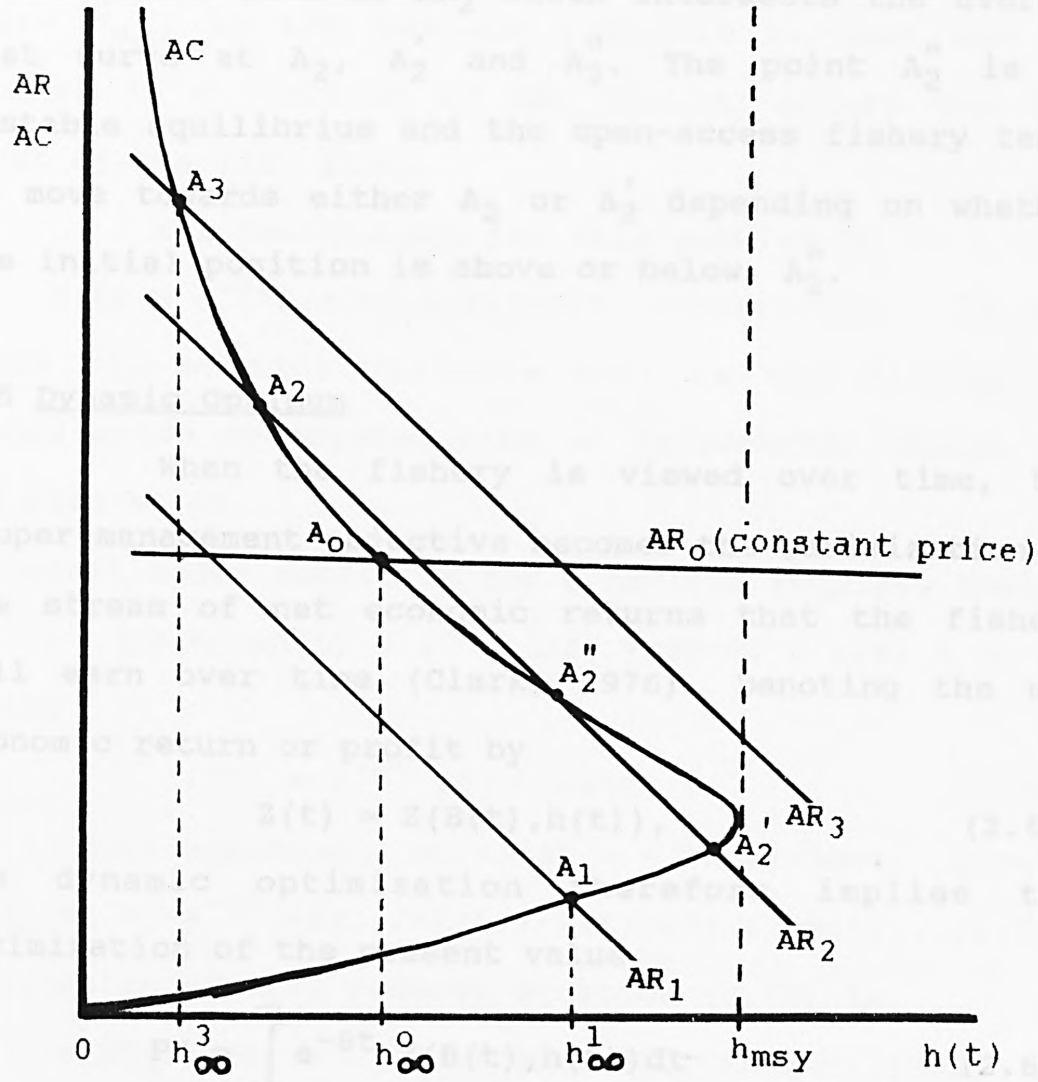


Figure 2.14 Open-access equilibrium
(variable price)

is associated with a lower harvest level h_{∞}^{3} but a higher price level, $AR_3(h_{\infty}^{3}) > AR_1(h_{\infty}^{1})$. Consider a demand curve such as AR_2 which intersects the average cost curve at A_2, A_2' and A_2''. The point A_2'' is an unstable equilibrium and the open-access fishery tends to move towards either A_2 or A_2' depending on whether the initial position is above or below A_2''.

2.5 Dynamic Optimum

When the fishery is viewed over time, the proper management objective becomes the maximization of the stream of net economic returns that the fishery will earn over time (Clark, 1976). Denoting the net economic return or profit by

$$Z(t) = Z(B(t),h(t)), \tag{2.65}$$

the dynamic optimization therefore implies the maximization of the present value

$$PV = \int_{o}^{\infty} e^{-\theta t} Z(B(t),h(t))dt \tag{2.66}$$

subject to the state equation describing the change in the size of the fish stock,

$$dB(t)/dt = f(B(t)) - h(t) \tag{2.67}$$

and an initial condition (assumed known or given), B(0). The instantaneous social rate of discount is denoted by θ and is normally assumed to approach the market rate of interest when in equilibrium (Clark, 1976). The harvest rate, h(t) is the control

variable(*) assumed to satisfy the following constraint

$$0 \leqslant h(t) \leqslant h_{max} \qquad (2.68)$$

where h_{max} is the maximum possible harvest and in general is a function of the fishing effort and the level of the fish stock.

The Hamiltonian for this problem is

$$H(t) = e^{-\theta t} Z(B(t),h(t)) + L(t)[f(B(t)) - h(t)] \qquad (2.69)$$

where the adjoint variable L(t) is the discounted shadow price associated with an incremental change in the fish stock.

The first order condition for a maximum requires that

$$\partial H(t)/\partial h(t) = e^{-\theta t} \partial Z(.)/\partial h(t) - L(t) = 0,$$

giving

$$L(t) = e^{-\theta t} \partial Z(.)/\partial h(t) \; . \qquad (2.70)$$

The adjoint equation, $dL(t)/dt = - \partial H(t)/\partial B(t)$ gives

$$dL(t)/dt = -e^{-\theta t}\{\partial Z(.)/\partial B(t)\} - L(t)\{\partial f(.)/\partial B(t)\}. \qquad (2.71)$$

Elimination of L(t) reduces equation (2.71) to

$$-\theta\{\partial Z(.)/\partial h\} = - \partial Z(.)/\partial B - \{\partial Z(.)/\partial h\}\{\partial f(.)/\partial B\}$$

which simplifies to

$$\partial f/\partial B + \{\partial Z(.)/\partial B\}/\{\partial Z(.)/\partial h\} = \theta. \qquad (2.72)$$

Equation (2.72) is a fundamental equation for the basic bioeconomic model. The left hand side of the equation is termed the 'own rate of interest, of the resource. It is the sum of two terms, the rate of

---

(*) Under this assumption, the system is controlled by varying the rate of harvest. The fishing effort, E(t) could also be used as a control variable. The result would have been identical, but with a more cumbersome algebra (Clark, 1975; Clark and Munro, 1979).

change in net growth associated with an increment in the fish stock and the marginal stock effect. Thus, equation (2.72) states that the optimal stock level is that level where the own rate of interest of the resouce stock equals the social rate of discount.

Now, the economic profit is given by

$$\left.\begin{aligned} Z(t) &= \{p - c/[qB(t)]\}h(t) \\ &= \{p - C(B(t))\}h(t) \end{aligned}\right\} \quad (2.73)$$

where total revenue, $TR = ph(t)$,

total cost, $TC = cE(t)$

$= C(B(t)).h(t)$ (2.74)

and $h(t) = qE(t)B(t)$.

The term $C(B(T)) = c/[qB(t)]$ (2.75)

is the cost per unit of harvest and is an inverse function of the fish stock B(t). As the stock level decreases, the unit cost of harvest increases indicating that harvesting becomes more expensive as the stock depletes, and vice versa.

For a model with an infinite price elasticity of demand (constant price), we have

$$\begin{aligned} \partial Z/\partial B &= -[\partial C(B)/\partial B].h(t) \\ &= -[\partial C(B)/\partial B].f(B), \\ \partial Z/\partial h &= p - C(B) \end{aligned} \quad (2.76)$$

where in a steady state, $dB(t)/dt = 0$ and $h(t) = f(B)$.

Equation (2.72) then implies an optimal stock level B* such that

$$\left[\frac{\partial f}{\partial B} - \frac{[\partial C/\partial B].f(B)}{p - C(B)}\right]_{B = B^*} = \theta \quad (2.77)$$

which can also be written as

$$\left[\frac{(\partial/\partial B)\{[p - C(B)].f(B)\}}{p - C(B)}\right]_{B = B^*} = \theta \qquad (2.78)$$

which is simply

$$[\partial Z/\partial B]/[p - C(B)]\Big|_{B=B^*} = \theta \ . \qquad (2.79)$$

If $\theta = 0$, the optimal stock level B^* is the level where the own rate of interest is zero, that is where $\partial Z/\partial B = 0$. This corresponds to the level of maximum economic yield, B_{mey}. If in addition, the harvesting cost is independent of the stock level (for example zero harvesting cost), equation (2.77) then reduces to $\partial f/\partial B = 0$ which corresponds to the level associated with the maximum sustainable yield, B_{msy}. On the other extreme, if we allow $\theta \rightarrow \infty$, equation (2.79) implies $p - C(B) = 0$ which corresponds to the open-access bioeconomic equilibrium level, B_{∞}. Thus,

$$B^* = \begin{cases} B_{mey} & \text{if } \theta = 0 \\ B_{msy} & \text{if } \theta = 0 \text{ and } C \neq C(B) \\ B_{\infty} & \text{if } \theta \rightarrow \infty \ . \end{cases} \qquad (2.80)$$

The optimal stock level, B^* then lies somewhere between the levels of maximum economic yield, B_{mey} and zero economic profit (open-access bioeconomic equilibrium), B_{∞} for positive discount rate, $0 < \theta < \infty$. However, in relation to the level of maximum sustainable yield, B_{msy}, the optimal population stock level, B^* can in general be either greater than, equal to or less than B_{msy}. To see this, rewrite equation

(2.77) as

$$\left.\frac{\partial f(B)}{\partial B}\right|_{B=B^*} = \theta + \left.\frac{[\partial C(B)/\partial B].f(B)}{p - C(B)}\right|_{B=B^*} \qquad (2.81)$$

$$= \theta - S \ ,$$

where

$$S = -\{[\partial C(B)/\partial B].f(B)\}/\{p-C(B)\}\Big|_{B=B^*} \qquad (2.82)$$

is the marginal stock effect. It therefore follows that

$$B^* \begin{cases} < B_{msy} & \text{if } \theta > S \\ = B_{msy} & \text{if } \theta = S \\ > B_{msy} & \text{if } \theta < S \end{cases} \qquad (2.83)$$

provided that $p > C(B)$, that is it is profitable to harvest.

For the Schaefer's surplus production model where

$$f(B) = rB(1 - B/B_k) \quad \text{and} \quad C(B) = c/(qB) \ ,$$

the optimal steady state can be defined in terms of two equation system:

$$h = \phi(B) = \{\theta - r(1-2B/B_k)\}B\{qpB/c - 1\} \qquad (2.84)$$

and

$$h = rB(1 - B/B_k). \qquad (2.85)$$

This leads to a quadratic equation whose positive root is the unique optimal stock level B* (Clark, 1976) which depends on the bioeconomic parameters r, c, p, q, θ and B_k according to

$$B^* = (1/4)B_k\{m + \sqrt{m^2 + 8c\theta/(qprB_k)}\} \qquad (2.86)$$

where

$$m = 1 - (\theta/r) + c/(qpB_k). \qquad (2.87)$$

Equation (2.84) is called the 'catch locus' while equation (2.85) is the usual sustainable yield curve. Five different catch loci, $\phi_i(B)$, i=1,..,5 and a sustainable yield curve are depicted in figure 2.15.

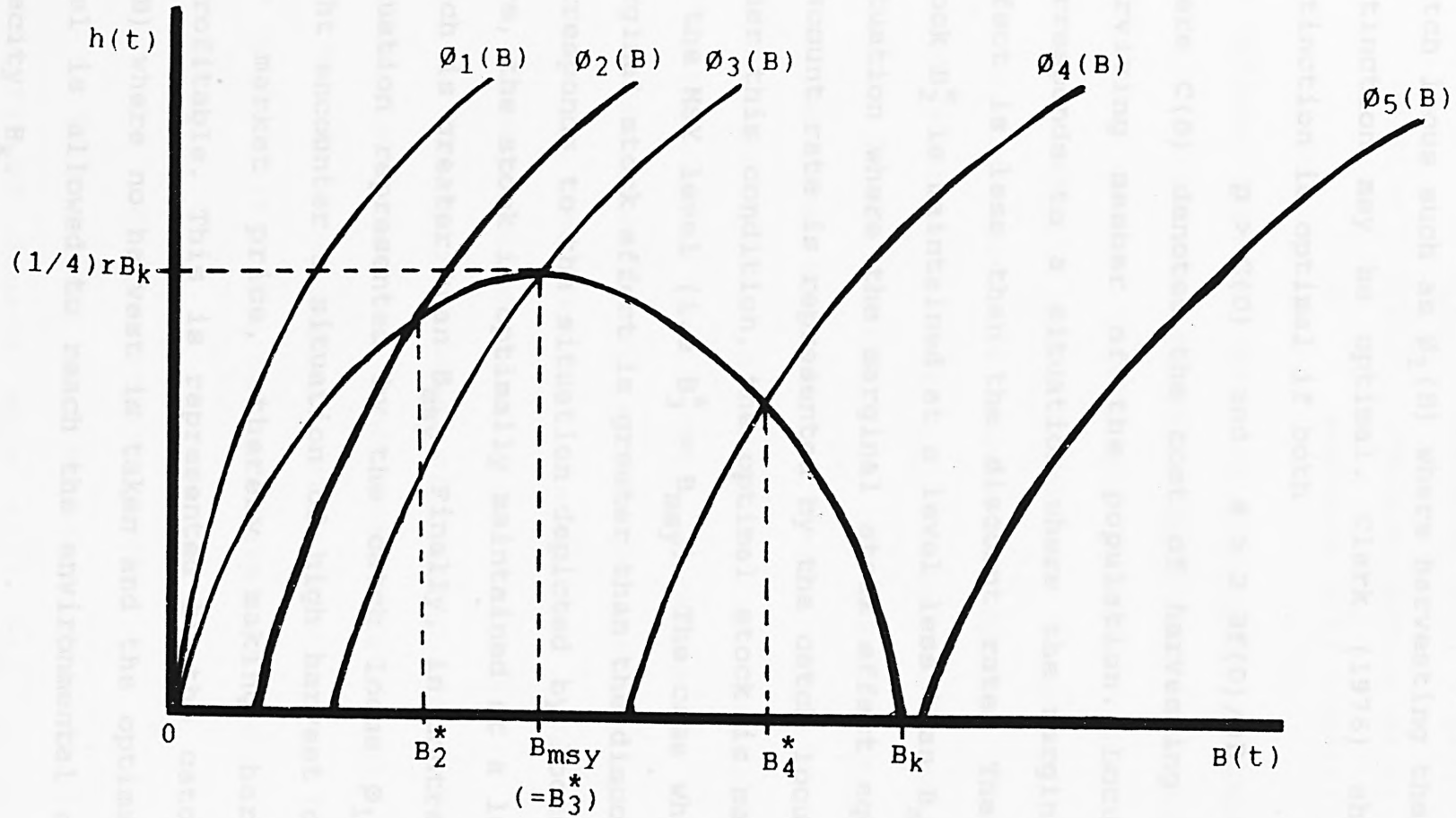


Figure 2.15 Catch loci and sustainable yield curve

A combination of high discount rate, low harvest cost and high market value might result in a catch locus such as $\emptyset_1(B)$ where harvesting the stock to extinction may be optimal. Clark (1976) shows that extinction is optimal if both

$$p > C(0) \quad \text{and} \quad \theta > 2\, \partial f(0)/\partial B$$

where C(0) denotes the cost of harvesting the last surviving member of the population. Locus $\emptyset_2(B)$ corresponds to a situation where the marginal stock effect is less than the discount rate. The optimal stock B_2^* is maintained at a level less than B_{msy}. The situation where the marginal stock effect equals the discount rate is represented by the catch locus $\emptyset_3(B)$. Under this condition, the optimal stock is maintained at the MSY level (i.e $B_3^* = B_{msy}$). The case where the marginal stock effect is greater than the discount rate corresponds to the situation depicted by locus $\emptyset_4(B)$. Here, the stock is optimally maintained at a level B_4^* which is greater than B_{msy}. Finally, in contrast to a situation represented by the catch locus $\emptyset_1(B)$, we might encounter a situation of high harvest cost and low market price, thereby making harvesting unprofitable. This is represented by the catch locus $\emptyset_5(B)$ where no harvest is taken and the optimal stock level is allowed to reach the environmental carrying capacity B_k.

Once the optimal equilibrium stock level B*(t) has been determined, the optimal harvest policy

h*(t) can then be deduced as :

$$h^*(t) = \begin{cases} h_{max} & \text{whenever } B(t) > B^*(t) \\ f(B^*) & \text{whenever } B(t) = B^*(t) \\ 0 & \text{whenever } B(t) < B^*(t). \end{cases} \quad (2.88)$$

The optimal approach path in this case is therefore a combination of the singular path and the so called 'bang-bang' or the 'most rapid approach' path. 'Disinvestment' should take place as soon as possible whenever the stock is above the optimal level. The maximum feasible harvest h_{max} is applied so as to drive the stock level towards B*(t) as quickly as possible. If, on the other hand, B(t) < B*(t), then 'investment' should take place as rapidly as possible. The harvesting ceases until B(t) increases to B*(t). As soon as the stock level reaches the optimal equilibrium level B*(t), the harvest rate is set equal to f(B*) which corresponds to the singular control.

The optimal level of fishing effort E*(t) can be determined from the functional relationship between h, E and B. For fishery with production function h(t) = qE(t)B(t), the optimal level of fishing effort is given by

$$E^*(t) = h^*(t)/\{qB^*(t)\}. \quad (2.89)$$

In the case of a market with a finite price elasticity of demand such that the price is a decreasing function of the harvest the maximization of the stream of economic returns from fishery over time

implies the maximization of the discounted present value

$$PV = \int_0^\infty e^{-\theta' t}.\{P(h).h - C(B).h\}dt \qquad (2.90)$$

subject to the same constraints as before. The rate of discount in this case is denoted by θ'.

Following similar approach as before, we arrive at

$$\left[\frac{\partial f}{\partial B} - \frac{(\partial C/\partial B).f(B)}{MR(h) - C(B)}\right]_{B=B^{*}_{\theta'}} = \theta' \qquad (2.91)$$

for the optimal equilibrium stock level $B^{*}_{\theta'}$, and where

$$MR(h) = \partial[P(h).h]/\partial h$$
$$= P(h) + h.(\partial P(h)/\partial h) \qquad (2.92)$$

is the marginal revenue generated by the fishery.

Since the marginal revenue MR(h) is always less than the average revenue AR = P(h), $(\partial P(h)/\partial h < 0)$ equations (2.72) and (2.91) imply that the optimal stock level for the case of constant price is less than that of variable price, provided $\theta' = \theta$, that is to say

$$B^{*}(t) < B^{*}_{\theta'}(t), \quad (\theta' = \theta) \qquad (2.93)$$

In this case the resource tends to be more conserved and is said to be underproduced.

If $\theta' = 0$ and $C \neq C(B)$, equation (2.91) reduces to $\partial f/\partial B = 0$ which corresponds to the level associated with the maximum sustainable yield, B_{msy}.

Rewriting equation (2.91) as

$$\left.\frac{(\partial f/\partial B)(\partial Z/\partial h) - (\partial C/\partial B).f(B)}{\partial Z/\partial h}\right|_{B=B^{*}_{\theta'}} = \theta', \qquad (2.94)$$

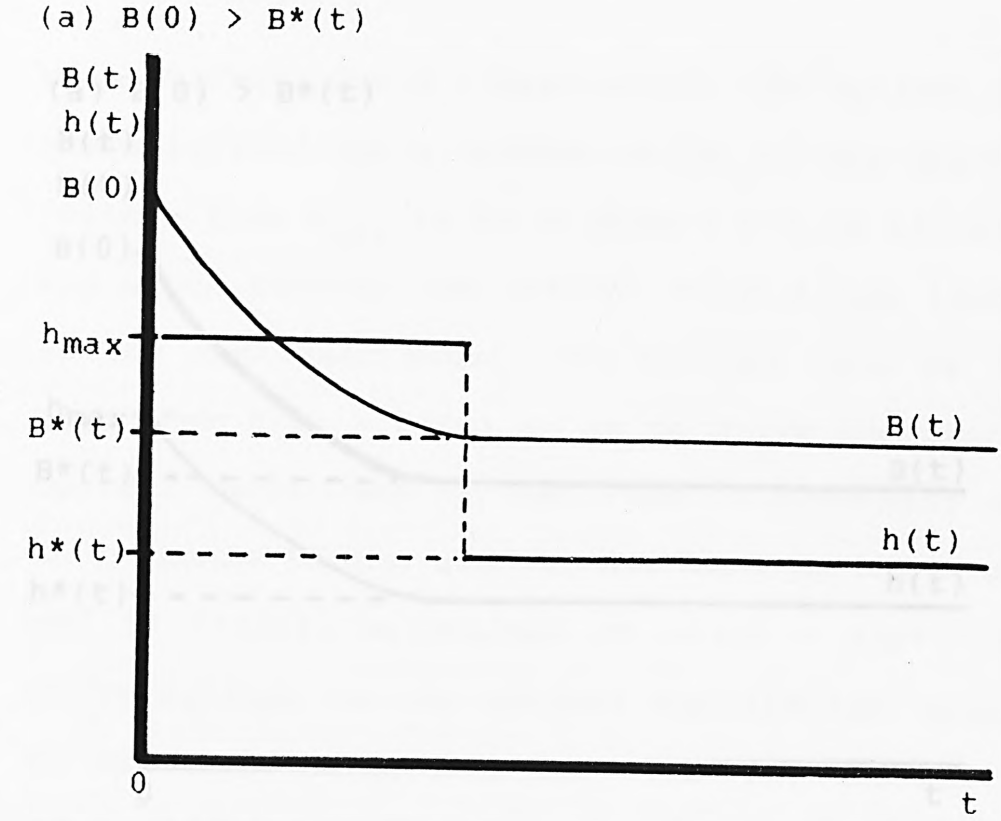
since $\partial Z/\partial h = MR(h) - C(B)$,

we see that as $\theta' \rightarrow \infty$, $\partial Z/\partial h \rightarrow 0$. Now, $\partial Z/\partial h = 0$ is one of the necessary conditions for the static maximum economic profit. It thus appears that in this case of finite price elasticity of demand (normally referred by economists as the 'monopoly' case) the tendency is to produce (that is harvest) at the level of maximum economic profit, MEY as the discount rate increases infinitely. This is in contrast to the linear case of infinite price elasticity of demand (constant price) where the tendency is towards the open-access bioeconomic equilibrium as the discount rate approaches infinity. Thus,

$$B^{*}(t) = \begin{cases} B_{msy} & \text{if } \theta' = 0 \text{ and } C \neq C(B) \\ B_{mey} & \text{if } \theta' \rightarrow \infty. \end{cases} \qquad (2.95)$$

The optimal path or rate of adjustment from an initial stock level $B(0) \neq B^{*}(t)$ requires the adjustment in the harvest rate (or alternatively the fishing effort). We have seen that for a fishery model with constant price and linear in harvest rate, the optimal path is a combination of singular and the most rapid approach paths. However, for a nonlinear model with finite price elasticity of demand, the approach path from an initial stock level to the optimal stock level $B^{*}(t)$ is more gradual (Clark, 1985).

These optimal paths for linear and nonlinear models are depicted in figures (2.16) and (2.17)



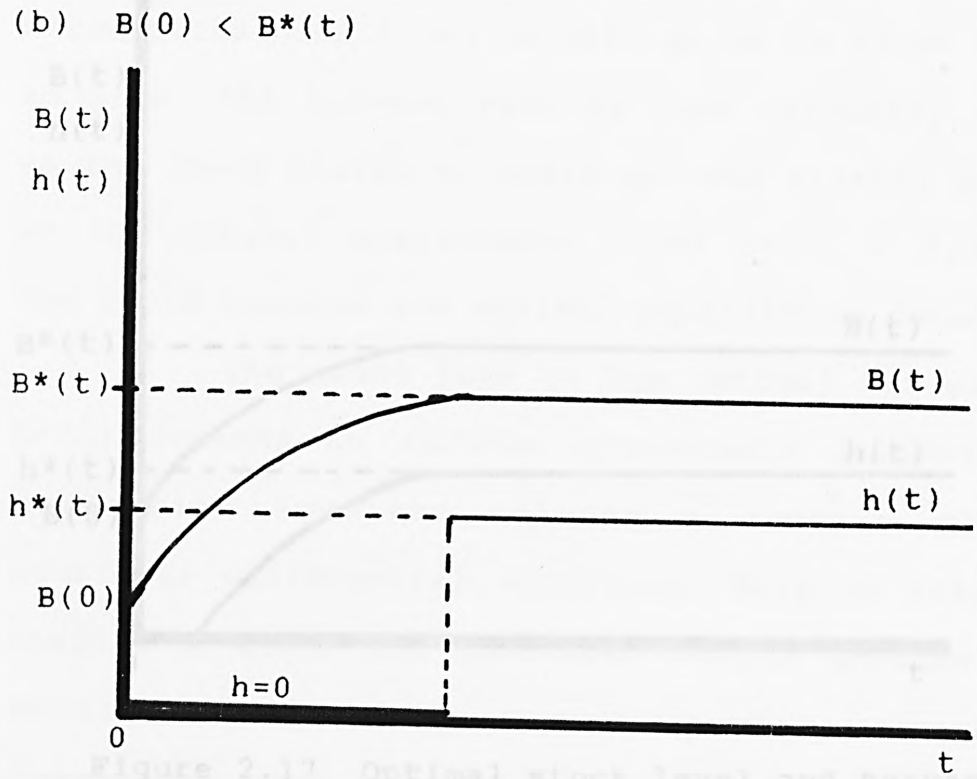


Figure 2.16 Optimal stock level and harvest rate (linear model)

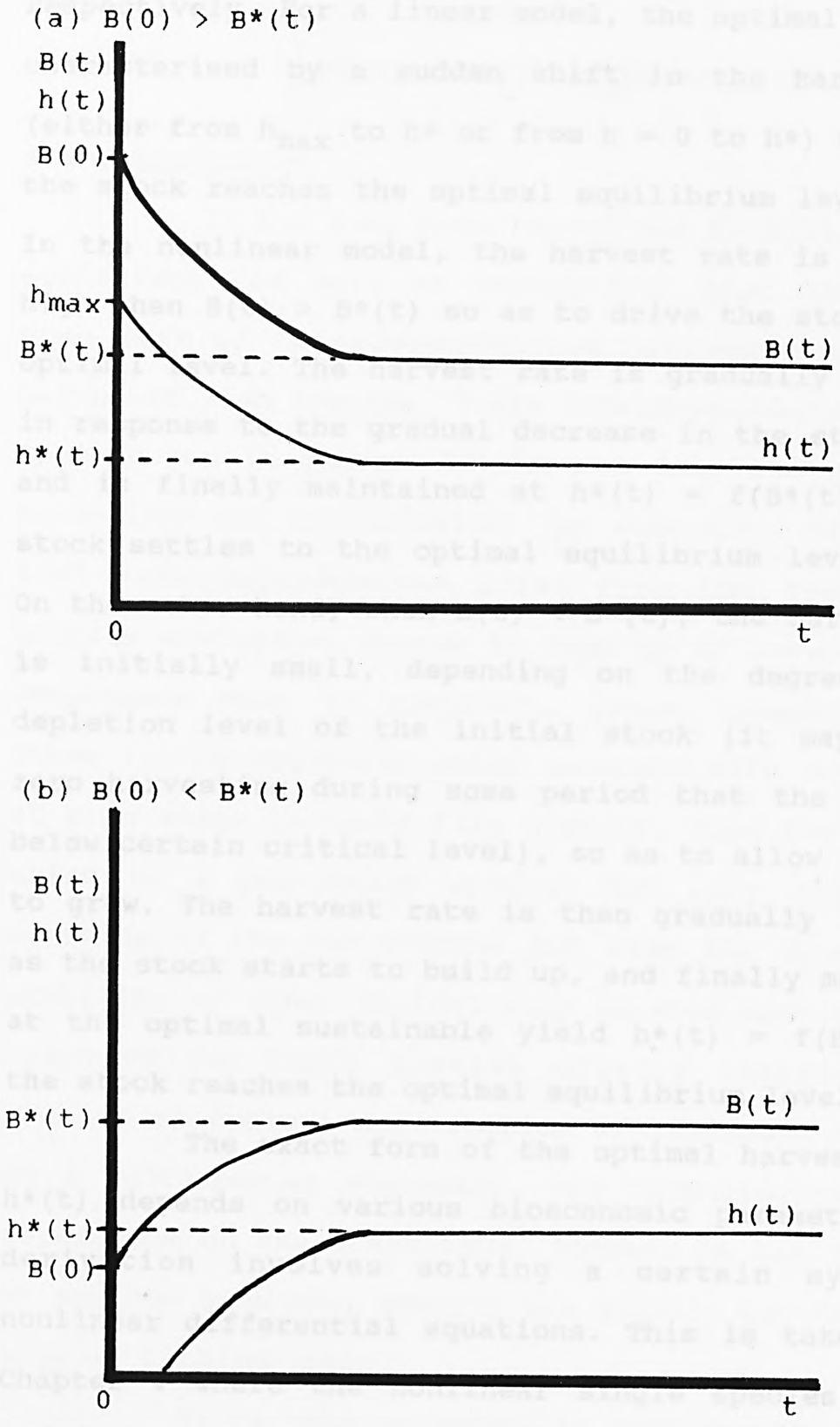


Figure 2.17 Optimal stock level and harvest rate (nonlinear model)

respectively. For a linear model, the optimal policy is characterised by a sudden shift in the harvest rate (either from h_{max} to h* or from h = 0 to h*) as soon as the stock reaches the optimal equilibrium level B*(t). In the nonlinear model, the harvest rate is initially high when B(0) > B*(t) so as to drive the stock to the optimal level. The harvest rate is gradually decreased in response to the gradual decrease in the stock level and is finally maintained at h*(t) = f(B*(t)) as the stock settles to the optimal equilibrium level B*(t). On the other hand, when B(0) < B*(t), the harvest rate is initially small, depending on the degree of the depletion level of the initial stock (it may involve zero harvesting during some period that the stock is below certain critical level), so as to allow the stock to grow. The harvest rate is then gradually increased as the stock starts to build up, and finally maintained at the optimal sustainable yield h*(t) = f(B*(t)) as the stock reaches the optimal equilibrium level B*(t).

The exact form of the optimal harvest policy h*(t) depends on various bioeconomic parameters. Its derivation involves solving a certain system of nonlinear differential equations. This is taken up in Chapter 4 where the nonlinear single species fishery model is extended to a multispecies ecosystem and formulated into a multi-dimensional optimal control problem solvable by numerical method.

CHAPTER 3

DYNAMIC MULTISPECIES MODEL

3.1 Introduction

It has long been recognised by biologists and ecologists (as well as economists) that there exist some form of interdependencies between commercially harvested fish species. These interdependencies between species can in general be divided into two classes — biological and technological (or economic). The biological interdependencies arise from the fact that a complex ecological system is made up of several living components such as predators, preys, competitors and other living organisms which interact with one another at some stage in their life history. Thus the exploitation of a particular species not only affects the dynamics of its own species but also the dynamics and stability of other biologically related species. These interactions among species greatly complicate the problem of optimal exploitation of renewable resources in a multispecies ecosystem. The technological interdependence on the other hand, focuses on the fact that at any one time many species are jointly harvested by a single fishing gear.

It is thus necessary to consider these interactions when analysing a multispecies fishery. However, considerations of biological interrelationships are not entirely new to multispecies analysis. Quirk and Smith

(1970) developed an optimal harvesting model involving possible biological interactions between species while Clark (1976) surveyed various multispecies models and briefly discussed some of the results.

A more specific biological interrelationships — predator-prey and competition — were discussed by Larkin (1963, 1966). The relationship between antarctic krill, a food source for many oceanic species, and predators such as Baleen Whale was studied by May et al (1979). The predator-prey relationship between predator species and shrimps in the German coastal water was examined by Tiews (1978a). In the same report, Tiews (1978b) also examined the disappearance of Bluefin tuna in the North Sea with expected ecological implications for herring and mackerel stocks.

Some major problems of multispecies fisheries were outlined and discussed by Gulland (1975) and documented further by Anon (1978).

The focus of this chapter is on the formulation of a multispecies fishery model which includes both of the above interdependencies. A simplified representation of the major biological and economic aspects of multispecies fishery is given in figure 3.1. As in a single species model, some of the biological aspects (such as environmental factors) are assumed to be approximately homogeneous and have minimum effect on the dynamics of the individual species. On the economic side of the model, factors such as imports and landings

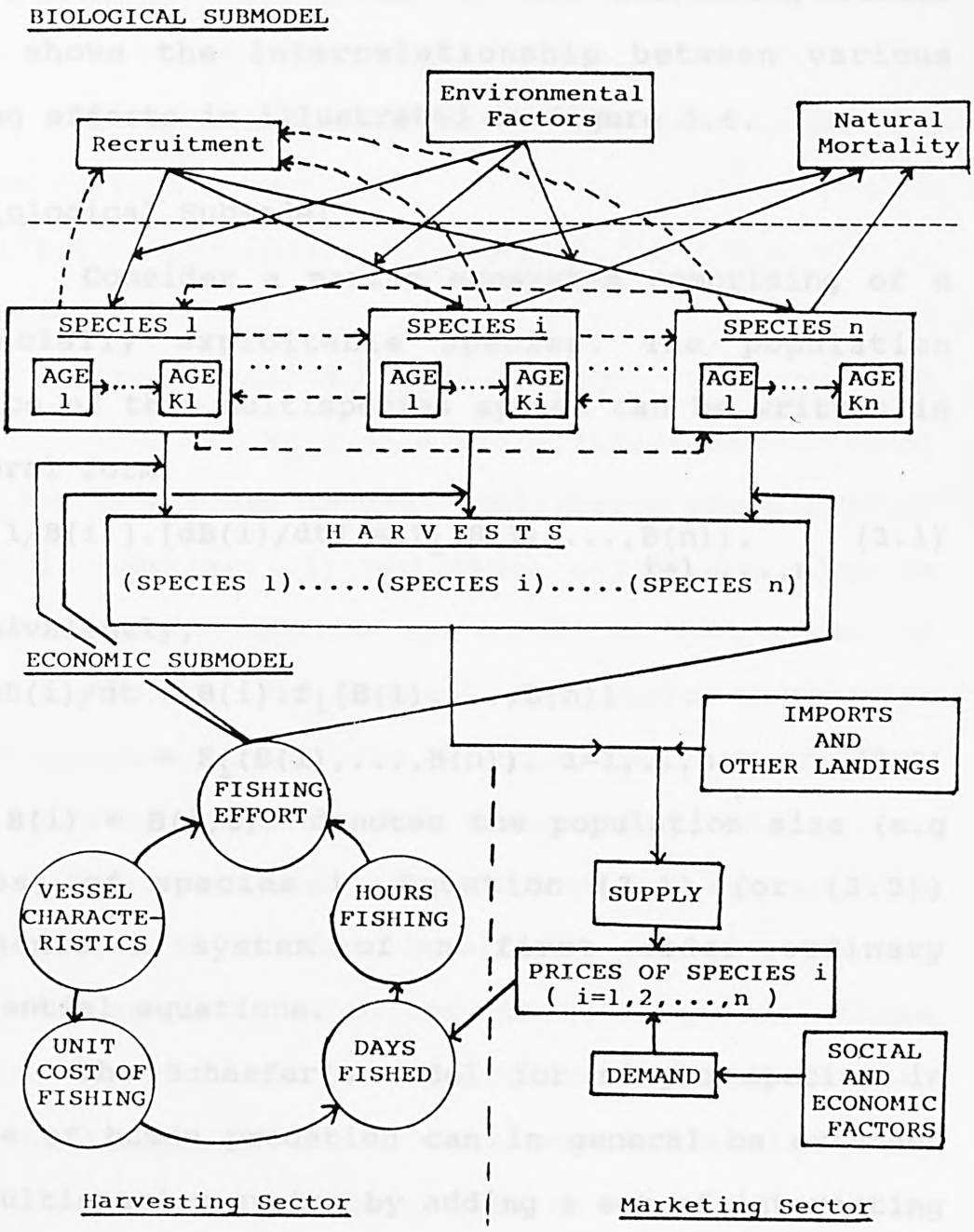


Figure 3.1 A simplified representation of the major biological and economic aspects of multispecies fishery.

from other fishing grounds are included whenever the available data and informations made it possible to do so. A more detailed model of the harvesting sector which shows the interrelationship between various fishing efforts is illustrated in figure 3.6.

3.2 Biological Submodel

Consider a marine ecosystem comprising of n commercially exploitable species. The population dynamics of this multispecies system can be written in a general form

$$[1/B(i)].[dB(i)/dt] = f_i(B(1),...,B(n)), \quad i=1,...,n \qquad (3.1)$$

or equivalently,

$$dB(i)/dt = B(i).f_i(B(1),...,B(n)) = F_i(B(1),...,B(n)), \quad i=1,..,n, \qquad (3.2)$$

where B(i) = B(i,t) denotes the population size (e.g biomass) of species i. Equation (3.1) (or (3.2)) represents a system of n first order ordinary differential equations.

The Schaefer's model for single species in absence of human predation can in general be extended to a multispecies system by adding a set of interacting terms such that the population dynamics is then described by a set of n differential equations

$$dB(i)/dt = r(i)B(i)\{1 - B(i)/K(i)\} + \sum_{j\neq i}^{n} a(i,j)B(i)B(j), \quad i=1,...,n \qquad (3.3)$$

where r(i) is the relative rate of growth of species i, K(i) is the single species environmental carrying

capacity for species i, and a(i,j) represents an interaction coefficient reflecting the effect of species j on species i ($j \neq i$) and can be positive, negative or zero.

At equilibrium, $dB(i)/dt = 0$, $(i=1,...,n)$ and equation (3.3) gives

$$r(i)\{1 - B_k(i)/K(i)\} + \sum_{j \neq i} a(i,j)B_k(j) = 0$$

which reduces to

$$B_k(i) = K(i) + \sum_{j \neq i} a_k(i,j)B_k(j) \qquad (3.4)$$

where $$a_k(i,j) = a(i,j)K(i)/r(i) \qquad (3.5)$$

and $B_k(i)$ is the new natural equilibrium stock size of species i. Thus $a_k(i,j)$ and hence a(i,j) can also be interpreted as a measure by which an individual of species j changes the natural equilibrium population size of species i from its (single species) environmental carrying capacity, K(i) (Sainsbury, 1982).

The biological interactions between any two species i and j can be classified according to the effect each species has on the other. In general there are three types of species interactions (Smith, 1975):

1. <u>competition (-,-)</u> where each species exhibits an inhibitive effect on the growth of the other and is denoted by $a(i,j) < 0$ and $a(j,i) < 0$;
2. <u>predator-prey (+,-)</u> where one species, the predator has an inhibitive effect on the growth of the other, the prey; the prey in turn exhibits an accelerating effect on the predator. This is denoted by

$$a(i,j) > 0 \text{ and } a(j,i) < 0 , \quad i \neq j$$

where species i is the predator and species j the prey.

3. <u>symbiotic or commensalism (+,+)</u> where each species exhibits an accelerating effect on the growth of the other and is denoted by $a(i,j) > 0$ and $a(j,i) > 0$. The case $a(i,j) = 0$ and $a(j,i) = 0$, $i \neq j$, is taken to imply no biological interaction exists between species i and species j.

As in a single species model, the impact of human exploitation is reflected by the addition of a harvesting term into the model such that the population dynamics now become

$$dB(i)/dt = r(i)B(i)\{1 - B(i)/K(i)\} + \sum_{j\neq i}^{n} a(i,j)B(i)B(j) - h(i), \quad i=1,\ldots,n \qquad (3.6)$$

The harvest rate of species i (=1,...,n) is denoted by

$$h(i) = Q(i)E(i)B(i) \qquad (3.7)$$

where Q(i) is the constant catchability coefficient associated with the harvesting of species i by the directed composite fishing effort E(i)(*). All other variables and parameters are as defined earlier.

Equation (3.6) thus becomes

$$dB(i)/dt = r(i)B(i)\{1-B(i)/K(i)\} + \sum_{j\neq i}^{n} a(i,j)B(i)B(j) - Q(i)E(i)B(i), \quad i=1,\ldots,n \qquad (3.8)$$

whose properties can best be analysed and illustrated by considering a two-species model.

(*) See section 3.3.2 for derivation of Q(i) and E(i) in the presence of technological interdependence.

3.2.1 The Competitive Case (-,-)

Consider a model of interspecific competition between two species i and j ($i \neq j$) such that

$$\left.\begin{aligned} dB(i)/dt &= \{r(i)-B(i)/K'(i)-a'(i,j)B(j) \\ &\quad -Q(i)E(i)\}B(i), \\ dB(j)/dt &= \{r(j)-B(j)/K'(j)-a'(j,i)B(i) \\ &\quad -Q(j)E(j)\}B(j) \end{aligned}\right\} \quad (3.9)$$

where
$$\left.\begin{aligned} K'(.) &= K(.)/r(.), \\ a(i,j) &= -a'(i,j) < 0 \\ a(j,i) &= -a'(j,i) < 0 \end{aligned}\right\} \quad (3.10)$$

and $a'(i,j)$ and $a'(j,i)$ are both positive.

Thus

$$\partial\dot{B}(i)/\partial B(j) = (\partial/\partial B(j)(dB(i)/dt) = -a'(i,j).B(i) < 0 , \quad (3.11)$$

and

$$\partial\dot{B}(j)/\partial B(i) = (\partial/\partial B(i)(dB(j)/dt) = -a'(j,i).B(j) < 0. \quad (3.12)$$

Equations (3.11) and (3.12) imply that an increase (decrease) in one species decreases (increases) the growth rate of its competitor.

At equilibrium, $\dot{B}(.) = dB(.)/dt = 0$, and for $B(.) \neq 0$, we then have

$$\dot{B}(i) = 0 : \quad 0 = r(i)-B(i)/K'(i)-a'(i,j)B(j)-Q(i)E(i)$$

$$\dot{B}(j) = 0 : \quad 0 = r(j)-B(j)/K'(j)-a'(j,i)B(i)-Q(j)E(j)$$

which further yield the following isoclines,

$$\left.\begin{aligned} B(i) &= K'(i)\{-a'(i,j)B(j)+[r(i)-Q(i)E(i)]\} \\ B(j) &= K'(j)\{-a'(j,i)B(i)+[r(j)-Q(j)E(j)]\} \end{aligned}\right\} \quad (3.13)$$

($B(i) = 0$ and $B(j) = 0$ are also isoclines)

The B(i) isocline cuts the B(i) axis at

$$B_E(i) = K'(i)[r(i)-Q(i)E(i)] \qquad (3.14a)$$

and the B(j) axis at

$$B_a(j) = [r(i)-Q(i)E(i)]/a'(i,j) \qquad (3.14b)$$

while the B(j) isocline intercepts the B(i) axis at

$$B_a(i) = [r(j)-Q(j)E(j)]/a'(j,i) \qquad (3.14c)$$

and the B(j) axis at

$$B_E(j) = K'(j)[r(j)-Q(j)E(j)]. \qquad (3.14d)$$

This gives rise to four classes of phase-planes depending on the relative magnitudes of $B_a(.)$ and $B_E(.)$ as illustrated in figure 3.2. The signs of $\dot{B}(i)$ and $\dot{B}(j)$ are given in each of the three or four regions which are divided by the isoclines. The arrows indicate the directions of the growth of each species in each region.

Figures 3.2(a) and 3.2(b) are associated with cases where $B_a(.) > B_E(.)$ and $B_E(.) > B_a(.)$ respectively. The first case has a stable equilibrium with positive stocks of both species. Reductions in the fishing effort of one species increase the stock of that species which in turn reduces the stock of its competitor. The intersection between the two isoclines in the second case is a saddle point and is thus unstable. The tendency for the system in this case is to converge to either one of the two stable equilibrium points, $(B_E(i),0)$ or $(0,B_E(j))$, involving the extinction of one of the species. For example, increases in fishing effort on species i will be advantageous to

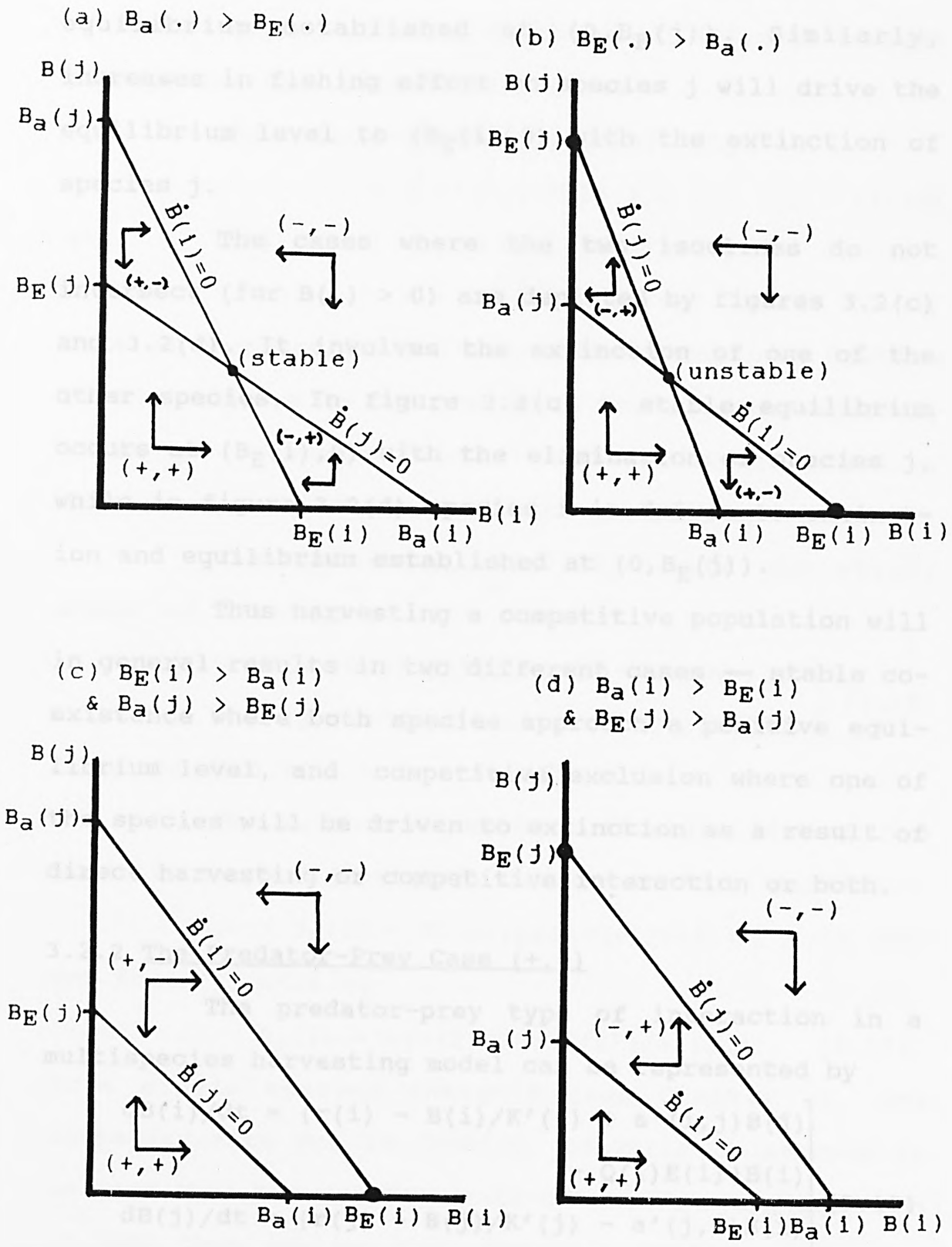


Figure 3.2 Competitive system isoclines

species j with species i being driven to extinction and equilibrium established at $(0,B_E(j))$. Similarly, increases in fishing effort on species j will drive the equilibrium level to $(B_E(i),0)$ with the extinction of species j.

The cases where the two isoclines do not intersect (for B(.) > 0) are depicted by figures 3.2(c) and 3.2(d). It involves the extinction of one of the other species. In figure 3.2(c) a stable equilibrium occurs at $(B_E(i),0)$ with the elimination of species j, while in figure 3.2(d) species i is driven to extinction and equilibrium established at $(0,B_E(j))$.

Thus harvesting a competitive population will in general results in two different cases — stable co-existance where both species approach a positive equilibrium level, and competitive exclusion where one of the species will be driven to extinction as a result of direct harvesting or competitive interaction or both.

3.2.2 The Predator-Prey Case (+,-)

The predator-prey type of interaction in a multispecies harvesting model can be represented by

$$\left.\begin{aligned} dB(i)/dt &= \{r(i) - B(i)/K'(i) + a'(i,j)B(j) \\ &\qquad - Q(i)E(i)\}B(i) \\ dB(j)/dt &= \{r(j) - B(j)/K'(j) - a'(j,i)B(i) \\ &\qquad - Q(j)E(j)\}B(j) \end{aligned}\right\} \quad (3.15)$$

where $a'(i,j)$ and $a'(j,i)$ are both positive and $K'(.) = K(.)/r(.)$. Here, species i is the predator and

species j the prey.

Differentiating equations (3.15) with respect to B(j) and B(i) respectively gives

$$\partial\dot{B}(i)/\partial B(j) = (\partial/\partial B(j))[dB(i)/dt]$$
$$= a'(i,j)B(i) > 0 , \qquad (3.16)$$

and
$$\partial\dot{B}(j)/\partial B(i) = (\partial/\partial B(i))[dB(j)/dt]$$
$$= - a'(j,i)B(j) < 0 . \qquad (3.17)$$

Thus an increase in the abundance of the prey species is advantageous to the growth of the predator species, while an increase in the predator species has a negative effect on the growth of the prey species.

The isoclines associated with the steady state are given by

$$\left.\begin{aligned} B(i) &= K'(i)\{a'(i,j)B(j)+[r(i)-Q(i)E(i)]\} \\ B(j) &= K'(j)\{-a'(j,i)B(i)+[r(j)-Q(j)E(j)]\} \end{aligned}\right\} \qquad (3.18)$$

together with $B(i) = 0$ and $B(j) = 0$.

The B(i) isocline is a straight line with a positive slope $K'(i)a'(i,j)$ cutting the B(i) axis at

$$B_E(i) = K'(i)[r(i)-Q(i)E(i)] \qquad (3.19A)$$

and the B(j) axis at

$$B_a(j) = -[r(i)-Q(i)E(i)]/a'(i,j). \qquad (3.19B)$$

From single species analysis (see Chapter 2), the mortality rate due to fishing, Q(i)E(i) is assumed to be less than the relative rate of growth r(i). Equation (3.19B) then implies that the B(i) isocline cuts the prey axis at a negative level. If the fishing mortality rate Q(i)E(i) is greater than r(i) (for example by applying a sufficiently large fishing effort such that

$E(i) > r(i)/Q(i))$, the exploitation will drive the species to extinction regardless of the type of species interactions.

The B(j) isocline is also a straight line but with a negative slope cutting the B(j) axis at

$$B_E(j) = K'(j)[r(j)-Q(j)E(j)] \qquad (3.20A)$$

and the B(i) axis at

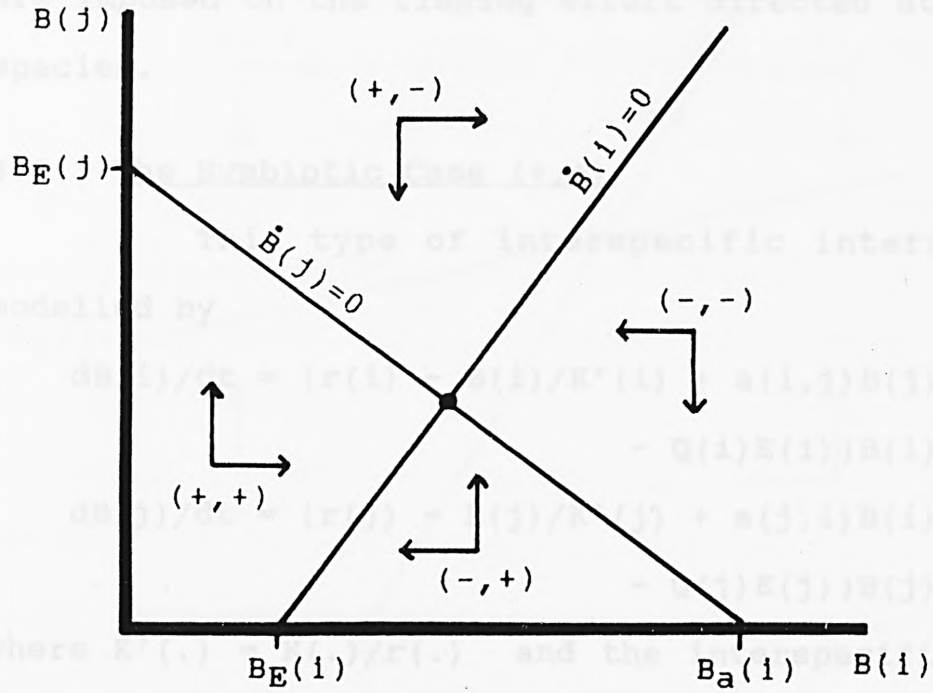
$$B_a(i) = [r(j)-Q(j)E(j)]/a'(j,i). \qquad (3.20B)$$

Thus, for $r(.) > Q(.)E(.)$ there corresponds two types of phase planes depending on the relative magnitudes of $B_E(i)$ and $B_a(i)$.

The case of $B_a(i) > B_E(i)$ is depicted in figure 3.3(a) where a stable steady state solution is established at the intersection of the two isoclines. Increases in the fishing effort directed at the predator will move the steady state solution along the B(j) isocline towards a lower predator stock and a higher prey stock. However reduction in the fishing effort directed at the prey species not only drives the equilibrium to a larger prey stock but also to a larger predator stock along the B(i) isocline.

In the second case where $B_E(i) > B_a(i)$, the prey species is being driven to extinction and a short run equilibrium solution is established at $(B_E(i),0)$ as depicted in figure 3.3(b). However, in the long run, the predator species is also expected to approach extinction due to the absence of the prey, provided that it is entirely dependent on the prey as its

(a) $B_a(i) > B_E(i)$



(b) $B_E(i) > B_a(i)$

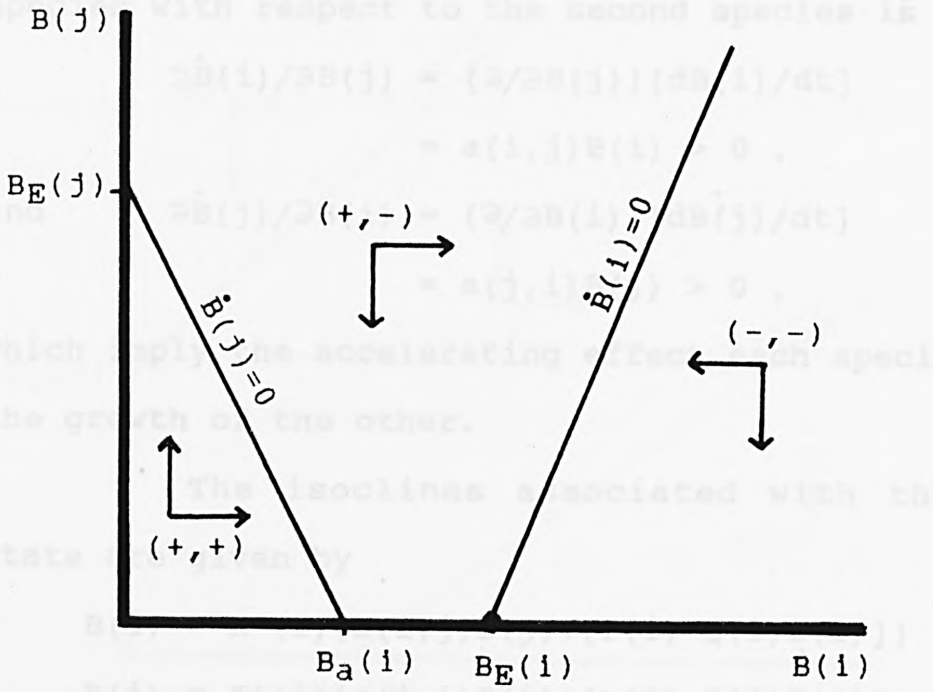


Figure 3.3 Predator-prey system isoclines
($r(.) > Q(.)E(.)$)

principal food source. In this situation, both stocks could perhaps be conserved if some upper constraints are imposed on the fishing effort directed at the prey species.

3.2.3 The Symbiotic Case (+,+)

This type of interspecific interaction is modelled by

$$\left.\begin{aligned} dB(i)/dt &= \{r(i) - B(i)/K'(i) + a(i,j)B(j) \\ &\qquad - Q(i)E(i)\}B(i) \\ dB(j)/dt &= \{r(j) - B(j)/K'(j) + a(j,i)B(i) \\ &\qquad - Q(j)E(j)\}B(j) \end{aligned}\right\} \quad (3.21)$$

where $K'(.) = K(.)/r(.)$ and the interspecific species interaction coefficients $a(i,j)$ and $a(j,i)$ are both positive. The rate of change of the growth of one species with respect to the second species is given by

$$\partial\dot{B}(i)/\partial B(j) = (\partial/\partial B(j))[dB(i)/dt]$$
$$= a(i,j)B(i) > 0 , \qquad (3.22A)$$

and

$$\partial\dot{B}(j)/\partial B(i) = (\partial/\partial B(i))[dB(j)/dt]$$
$$= a(j,i)B(j) > 0 , \qquad (3.22B)$$

which imply the accelerating effect each species has on the growth of the other.

The isoclines associated with the steady state are given by

$$\left.\begin{aligned} B(i) &= K'(i)\{a(i,j)B(j)+[r(i)-Q(i)E(i)]\} \\ B(j) &= K'(j)\{a(j,i)B(i)+[r(j)-Q(j)E(j)]\} \end{aligned}\right\} \quad (3.23)$$

together with $B(i) = 0$ and $B(j) = 0$.

Both isoclines are straight lines with positive slopes,

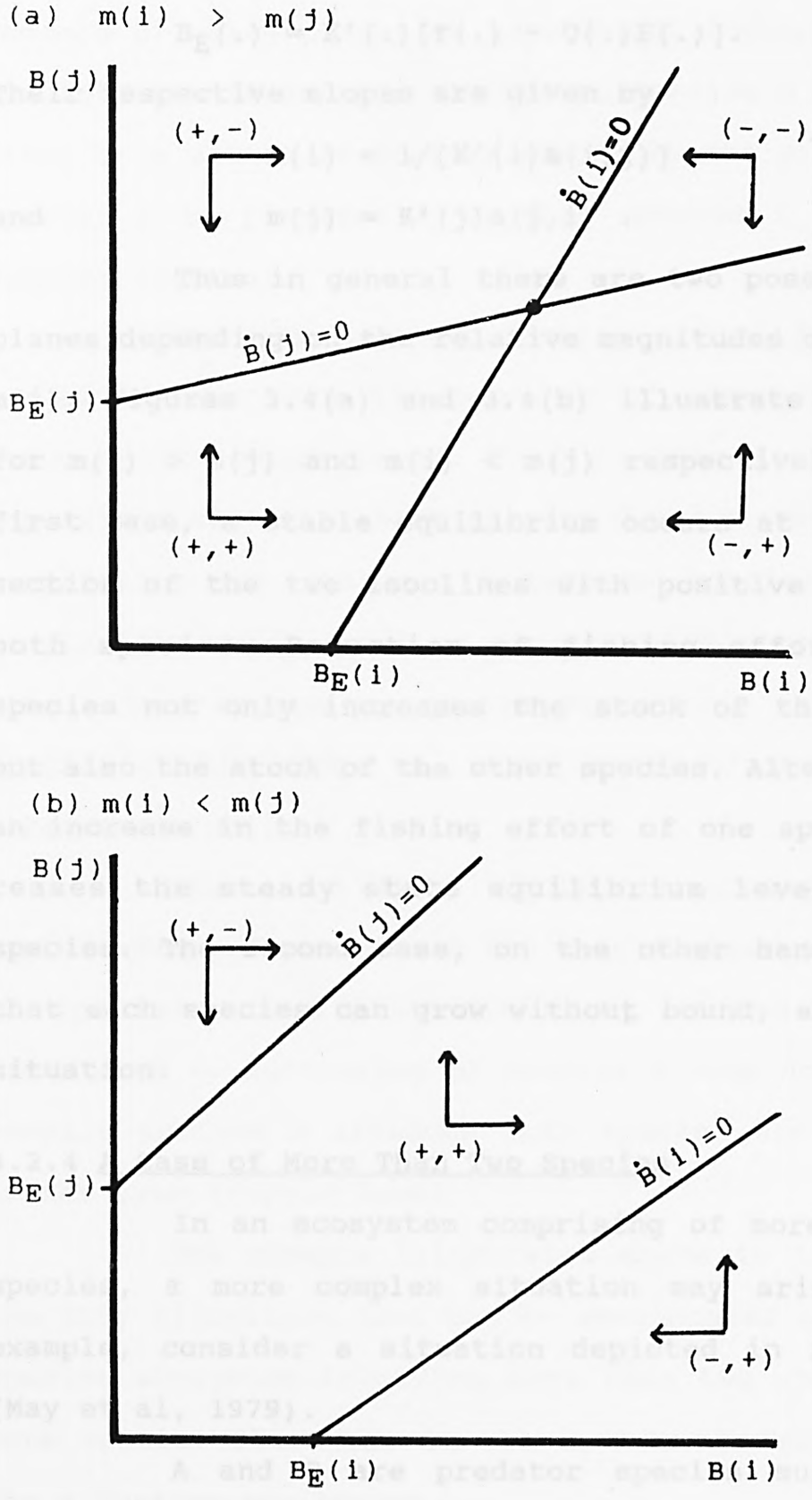


Figure 3.4 Symbiotic system isoclines
(r(.) > Q(.)E(.))

each cutting its own axis at

$$B_E(.) = K'(.)[r(.) - Q(.)E(.)]. \qquad (3.24)$$

Their respective slopes are given by

$$\left.\begin{aligned} m(i) &= 1/[K'(i)a(i,j)] \\ \text{and} \quad m(j) &= K'(j)a(j,i) \ . \end{aligned}\right\} \qquad (3.25)$$

Thus in general there are two possible phase planes depending on the relative magnitudes of m(i) and m(j). Figures 3.4(a) and 3.4(b) illustrate the cases for m(i) > m(j) and m(i) < m(j) respectively. In the first case, a stable equilibrium occurs at the intersection of the two isoclines with positive stocks of both species. Reduction of fishing effort on one species not only increases the stock of that species but also the stock of the other species. Alternatively, an increase in the fishing effort of one species decreases the steady state equilibrium level of both species. The second case, on the other hand, implies that each species can grow without bound, an unstable situation.

3.2.4 A Case of More Than Two Species

In an ecosystem comprising of more than two species, a more complex situation may arise. As an example, consider a situation depicted in figure 3.5 (May et al, 1979).

A and B are predator species such that A preys on both species C and D which are competing for the resource E, while B preys only on species D. The

competitive nature between C and D is such that in the absence of other predation, species C dominates and in the long run is capable of driving species D to extinction. This effect is however offset by the predation of species C by predator A so that species C and D can coexist together.

Now suppose that fishing effort is utilised so as to increase the harvest of species A, thus reducing its stock level. This in turn increases the population stocks of both species C and D. However, the competition for resource E between species C and D reduces the stock level of species D. But species D is also a food source for the predator B. A reduction in species D will cause the stock level of species B to decrease as well.

Thus, in this situation increasing the exploitation of predator A not only decreases the stock of species A but also the stock of the competing predator B — harvesting of species A does not actually benefit species B although both species are competing at the same trophic level.

The example illustrated above is just one of the many situations that can be encountered in a multi-species ecosystem involving more than two species. The more species there are in the system the more complex the situation may become.

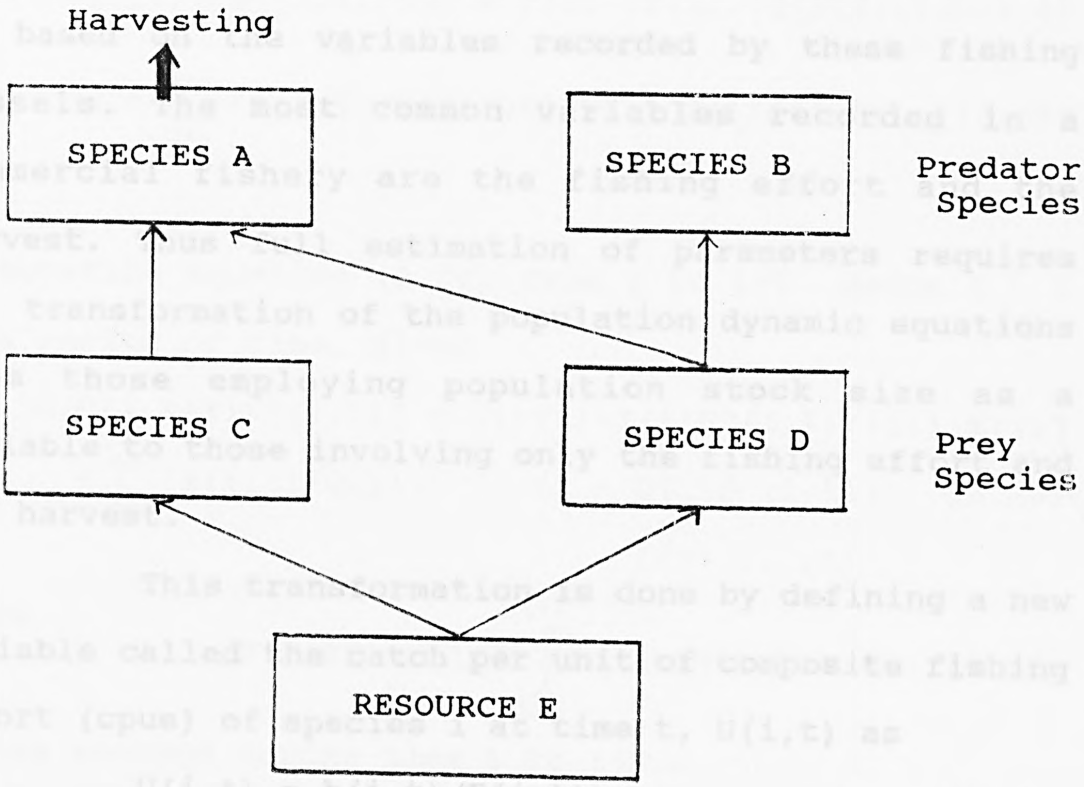


Figure 3.5 Four-species model

3.2.5 Estimation of Parameters

A complete numerical knowledge of all the parameters is required before any reasonable estimation of the population stock can be made. Since most fishery data available are those provided by the commercial fishing vessels, any estimation done should therefore be based on the variables recorded by these fishing vessels. The most common variables recorded in a commercial fishery are the fishing effort and the harvest. Thus full estimation of parameters requires the transformation of the population dynamic equations from those employing population stock size as a variable to those involving only the fishing effort and the harvest.

This transformation is done by defining a new variable called the catch per unit of composite fishing effort (cpue) of species i at time t, U(i,t) as

$$U(i,t) = h(i,t)/E(i,t), \quad E(i,t) \neq 0, \quad i=1,\ldots,n \qquad (3.26)$$

where h(i,t) = h(i) is the harvest of species i at time t and E(i,t) = E(i) is the composite fishing effort directed at species i at time t.

Using equation (3.9), we can further express U(i,t) as

$$U(i,t) = Q(i)B(i,t), \quad i=1,\ldots,n, \qquad (3.27)$$

where as before B(i,t) = B(i) is the total stock size of species i at time t.

Elimination of B(i) from equation (3.10)

yields

$$dU(i,t)/dt = r(i)U(i,t)\{1 - U(i,t)/[Q(i)K(i)]\} + \sum_{j\neq i} \{a(i,j)U(i,t)U(j,t)/Q(j)\} - Q(i)U(i,t)E(i,t) ,$$

which simplifies to

$$[1/U(i,t)][dU(i,t)/dt] = r(i) - \{r(i)/[Q(i)K(i)\}U(i,t) + \sum_{j\neq i} \{a(i,j)/Q(j)\}U(j,t) - Q(i)E(i,t), \quad (3.28)$$

$$(i=1,\ldots,n).$$

Integrating equation (3.28) from t to t+T where T > 0 is a period of time, gives

$$\ln[U(i,t+T)/U(i,t)] = T\{r(i) - r(i)U^{\wedge}(i,t)/[Q(i)K(i)] + \sum_{j\neq i} [a(i,j)/Q(j)]U^{\wedge}(j,t) - Q(i)E^{\wedge}(i,t)\}, \quad (3.29)$$

$$(i=1,\ldots,n)$$

where

$$F^{\wedge}(.t) = (1/T)\int_{t}^{t+T} F(.,t)dt, \; T > 0 \quad (3.30)$$

is the average during time t to t+T.

As it is, the left hand side of equation (3.29) refers to the 'instantaneous' catch per unit of fishing effort at the beginning of times t and t+T. This instantaneous quantity is not easy to measure. Nevertheless, since the total harvest and fishing effort during any period of time (for example annually) are generally available, we can redefine U(i,t) as the catch per unit of fishing effort of species i observed (or recorded) <u>during</u> period t.

Equation (3.30) defines the time average

F^(.,t) in a continuous framework. For commercial fishery with discrete time data on harvest and fishing effort, we can define the equivalent time average as

$$F^{\wedge}(.,t) = (1/T)\sum_{s=t}^{t+T-1} F(.,s)$$

$$= (1/T)\{F(.,t)+....+F(.,t+T-1)\}. \quad (3.31)$$

Equation (3.29) can further be written in a simpler form as (for i=1,...,n)

$$(1/T).\ln[U(i,t+T)/U(i,t)] = r(i) + \sum_{j=1}^{n} A(i,j)U^{\wedge}(i,t)$$

$$- Q(i)E^{\wedge}(i,t), \quad (3.32)$$

where

$$U(.,t) = h(.,t)/E(.,t), \quad E(.,t)\neq 0 , \quad (3.33)$$

$$U^{\wedge}(.,t) = (1/T)\{U(.,t)+...+U(.,t+T-1)\}, \quad (3.34)$$

$$E^{\wedge}(.,t) = (1/T)\{E(.,t)+...+E(.,t+T-1)\}, \quad (3.35)$$

$$A(i,i) = - r(i)/[Q(i)K(i)] \quad (3.36)$$

and $$A(i,j) = a(i,j)/Q(j), \quad i \neq j . \quad (3.37)$$

Thus, given complete informations on U(i,t), U^(i,t) and E^(i,t), equation (3.32) enables us to predict the future catch per unit of fishing effort U(i,t+T). The parameters r(i), K(i), Q(i) and a(i,j) can all be estimated, for example by linear regression using an ordinary least square method (OLSQ) for various values of T. It should be noted that as the value of T increases, the sample size for a fixed number of observations reduces and this could pose a serious problem especially when the number of species involved is large.

Perhaps the most popular estimation technique in applied research is the ordinary least squares, OLS estimator or method. The OLS estimator satisfies all the necessary requirements of the 'classical' linear regression model. This includes the assumptions that the expected value of the error term is zero; the error terms have a constant variance and are uncorrelated with each other; the dependent variable is a linear function of the independent variables plus a stochastic error term; if different samples were gathered, the observations on independent variables can be taken as fixed; and lastly there are no linear relationships between independent variables (multicollinearity).

Despite the ability of the OLS estimator to fulfil the requirements of the linear regression model, some econometric problems such as the possibility of bias, auto or serial correlation, multicollinearity and heteroscedasticity can still arise with the model and the data.

Whenever the values of the variables in a relationship are jointly determined by many (and sometimes opposing) forces, there exists a possibility of bias in the parameter estimates obtained by OLS. Further, in the case of simultaneous equations model where the variables simultaneously satisfy all the equations, using a single-equation procedure such as OLS to estimate the model introduces what is called a 'simultaneity' bias, and generally inconsistent

estimators because of the correlation between the error term and the various variables.

One solution to the existence and effect of simultaneity bias is to compare the estimations obtained from two different techniques —— the potentially biased OLS parameter estimates could be compared to 'consistent' estimates obtained by some other technique. If the differences were significant, and the consistent estimates were theoretically appropriate, the OLS estimates could be rejected and the presence of simultaneity bias established. However, this procedure is seldom possible with the (limited) available data. Any consistent estimation technique requires more informations, in the form of additional variables and data before any further estimations can be made.

Another alternative, if the available data is sufficient, is to divide the data set into two subsets or groups. The first group of data is used for parameter estimations by OLS while the second is used to test the 'goodness' (or the fitness) of the estimates. However, as before, this procedure is also subjected to the abundance of the data. In most applied research, the available data is normally 'just' sufficient for parameter estimations, and the 'goodness' of the regression is seldom tested. As a consequence, the possibility of simultaneity bias is normally either given less attention or ignored, and other statistics, for example the coefficient of multiple determination,

R^2 is taken as an approximate measure of the goodness of the regression.

Autocorrelation is a problem which occurs frequently in parameter estimations, especially when involving time-series data. It arises when the error terms in different observation of the variables are related. Thus, autocorrelation can be classified as either positive or negative, depending on how one error term in one period is associated with the error term in the next period. One of the major causes of autocorrelation is the omission of variable or variables. Additionally, it can also be due to the adoption of an incorrect functional form, for example applying a linear estimation to a curvilinear relationship. Thus, any given sample of the autocorrelated data may therefore generate over-estimates or under-estimates of the parameters.

The most frequent and popular test for autocorrelation is the Durbin-Watson statistic, D-W, which can assume a value from zero to four. A D-W value of exactly 2.0 suggests the absence of autocorrelation and is regarded as a good D-W statistic. Values greater or less than 2.0 are interpreted as indicating a potential autocorrelation problem. The zero to four range of values of the D-W statistic is further divided into five intervals —— two of these intervals suggest there is autocorrelation, one suggests there is no autocorrelation and the remaining two are the 'we don't know'

intervals. The boundaries of these five intervals are presented in the statistical tables and are dependent on the sample size and the number of the independent variables.

When two or more of the independent variables in an equation are highly correlated, there arise what is termed a multicollinearity problem. As with auto-correlation, the relationship between the correlated variables can be either positive or negative, resulting in difficulty when attempting to separate out the individual effect of each collinear independent variable.

One of the most important effects of multi-collinearity is the generation of unrealistically large standard errors on the estimated parameters. The magnitudes of these standard errors can be so large that the calculated t-statistics might be smaller than the critical t-statistics. Another problem of multi-collinearity lies on the sensitivity of the data set used in the estimation. The regression parameters estimated from one data set may differ from those estimated from another data set if multicollinearity is present with either. In addition, the results of the estimation will also depend greatly on the specification of the model being tested. An apparently minor change in the model that would normally produce very small or even negligible effects on the parameter estimates will generate significantly different results when independent variables are collinear. Although the

probability is low, it is possible in some cases for the regression parameters to be statistically insignificant (with low t-statistics) but to have a high coefficient of multiple determination, R^2.

Perhaps one of the most obvious and ideal ways of tackling the problem of multicollinearity is to obtain a different set of data of the same variables which do not exhibit multicollinearity, <u>if and when more data were available</u>. However, this never seems to be the case. An alternative way of avoiding multicollinearity, and which is frequently being adopted, is to use a 'second-best' solution where <u>all</u> the collinear variables are identified and excluded from the model. This extremely imperfect way of avoiding multicollinearity should not be done in a random fashion. The theoretical aspects and assumptions of the proposed model should be consulted and taken into consideration in deciding which variables to exclude. The normal approach is to keep the 'strongest' variable(s) (with respect to the assumptions adopted by the model) in the estimated equation. It is thus not far fetched to say that there is no real, genuine solution to the problem of multicollinearity. The above solutions are only the best that are usually suggested.

Another common problem associated with parameter estimations is that of heteroscedasticity which arises when the data set violate the assumption that the error terms all have the same variance. When this

happens, the error terms may be magnified or may tend to cancel out. In either situation, the variance of the error terms varies directly with the size of the error terms. If the variance is constant, the condition is known as homoscedasticity; if it is not constant, it is called heteroscedasticity and the OLS estimator is said to be inefficient (even though it might remain unbiased).

The major effect of heteroscedasticity, if it exists, is to cause the estimated parameters to be either too large or too small, depending on the exact pattern representing heteroscedasticity. If all variances are assumed to be of equal size and are given equal weight (as is done in OLS) then the large variances will be 'overweight' in their importance. The OLS estimator is thus no longer the 'best' estimator despite the variances still having a mean of zero and being normally distributed. The significance test and summary statistics associated with the OLS regression in this case are therefore incorrect.

The obvious remedy for this problem thus lies in determining the manner in which the variance of the error terms varies, applying weights of some sort to the importance of the error terms and then performing the appropriate generalised least square regression, GLS. The GLS estimator is considered to have smaller variance than the OLS estimator and is therefore regarded as the 'best' or alternatively the 'most

efficient' one.

However, there appear to be no definite agreement among econometricians concerning the exact weighting or as to when and even if, the GLS estimator should be used. The normal course taken by most researchers is to acknowledge the presence of heteroscedasticity, if it exists, but not to act on it. In other words, accept that the OLS estimator is not efficient but any damage done is minor and may be less than that caused by the inappropriate application of GLS.

Most of the problems discussed above are technical problems which are normally referred to as 'data' problems in the sense that they arise only for certain data set.

Now, returning to equation (3.22), observe that it can also be expressed in a general form

$$U(i,t+T) = F(U(i,t),U(j,t),E(i,t)), \quad (i,j=1,\ldots,n) \qquad (3.38)$$

or alternatively

$$\begin{aligned} h(i,t) &= E(i,t).F(U(i,t-T),U(j,t-T),E(i,t-T)) \\ &= G(U(i,t-T),U(j,t-T),E(i,t-T),E(i,t)), \end{aligned} \qquad (3.39)$$

where $h(i,t) = U(i,t)E(i,t)$ is the harvest of species i $(=1,\ldots,n)$ during the time period t. Equation (3.39) thus implies that the harvest of species i during any time or time period t is dependent on the catches per unit of fishing effort of species i and j T time

period(s) ago as well as on the composite fishing effort of species i during times t and t-T.

3.3 Economic Submodel

3.3.1 Fishing Effort

In any analysis of production, it is essential first to establish a production function which is defined as a technical relationship between the physical output and the inputs needed to produce it. The production function in fishery is obtained by considering the relation between the activities of the fishing industry and the fishing mortality generated. The amount of activity involved in exploiting a fish stock is measured in terms of 'fishing effort', a term widely used in determining the production function. This activity can be either in terms of its impact on the fish population or in terms of the factors giving rise to the activity. Cunningham and Whitmarsh (1980) gave two definitions of fishing effort:

1. effective fishing effort which is associated with fishing mortality and is normally measured as the biomass of fish exploited by fishing expressed as a proportion of the mean population size,
2. nominal fishing effort which refers to the volume of resources devoted to fishing, quantified either in monetry or physical units.

Based on these two definitions, the economic concept of input in fishery is more closely related to

the nominal fishing effort. Thus, unless otherwise stated, the term fishing effort in this study refers to the nominal fishing effort as defined above. It may be regarded as a factor of production and is normally represented by either a single input such as the number of boats, the number of traps, the time spent fishing, and so on, or a composition of inputs that can include labour, for example number of fishermen, capital and all other factors involved in the exploitation of the fish stock.

In view of the numerous units that have been suggested and used in measuring the fishing effort, we can say that there is no such thing as a 'single correct unit' of fishing effort for a given type of fishing gear. Various criteria have been employed in deciding the 'best' unit of fishing effort to be used. This includes the knowledge of how the fishery operates, what changes occur in the fishery, the vessels in operation, the types of gear used, the strategy of the fishermen, as well as the nature of the fish stock itself.

This study looks at two measures of fishing effort — the number of hours fishing and the ton-hours fishing. The choice of the hours fishing is mainly due to its popularity as a measure of fishing effort in most studies in fishery science. Ton-hours fishing used in this study is defined as the product of the average gross registered tonnage (GRT) of the fishing vessel

and the number of hours it spent fishing. This choice is motivated by the desire to include the fishing power of the vessel in measuring the fishing effort, whereby the fishing power is assumed to be approximately proportional to the average GRT of the vessel.

3.3.2 Production Function

We have seen in section 2.2.2 that the total harvest of a fishing fleet is a function of the fish stock and the activity of fishing, the fishing effort. In a multispecies fishery, this can in general be expressed as

$$h(i,t) = g(E(i,t),B(i,t)), \quad i=1,\ldots,n \qquad (3.40)$$

where $h(i,t)$ is the harvest of species i at time t, $E(i,t)$ is the fishing effort 'directed at species i' at time t, and $B(i,t)$ is the stock size of species i at time t.

As in a single species analysis of Chapter 2, we will continue to assume that the production function (3.40) is of the form

$$h(i,t) = q(i)E(i,t)B(i,t), \quad i=1,\ldots,n \qquad (3.41)$$

where $q(i)$ is the constant catchability coefficient associated with the harvesting of species i.

By expressing the harvest as a proportion of the stock size, we can establish the relation between the effective fishing effort or fishing mortality of species i, $F(i,t)$ at time t and the nominal fishing

effort E(i,t) as

$$F(i,t) = q(i)E(i,t), \quad i=1,\ldots,n. \qquad (3.42)$$

Substituting equation (3.42) into equation (3.41), gives

$$h(i,t) = F(i,t)B(i,t), \quad i=1,\ldots,n \qquad (3.43)$$

which expresses the harvest as the product of the fishing mortality and the size of the fish stock.

Rearranging equation (3.41), we obtain

$$\begin{aligned} U(i,t) &= h(i,t)/E(i,t), \quad E(i,t) \neq 0 \\ &= q(i)B(i,t), \quad i=1,\ldots,n \end{aligned} \qquad (3.44)$$

which has earlier been defined as the catch per unit of (nominal) fishing effort (abbreviated cpue) of species i. It is a measure of the productivity or efficiency with which a given input E(i,t) is converted into output h(i,t) at (or during) time t, and is linearly dependent on the stock size B(i,t). The larger the stock size the more efficient is the fishery (larger cpue) and vice versa.

So far, the production function given by equation (3.41) assumes that only a single fishing effort E(i,t) is employed in exploiting species i. But in a real fishery world, fishing effort comprises of many types of fishing vessels and gears, each capable of harvesting more than one species. Thus while harvesting for species i, another species j ($\neq$i) is also being caught. Similarly, a different fishing

vessel employing a different type of fishing gear, while harvesting species j ($\neq$i) may also catch a third species k ($\neq$i,j). This 'mobility' of fishing effort is referred to as 'technological or economic interdependence' (see figure 3.6).

A bioeconomic multispecies model should therefore include not only the effects of biological interdependence but also the effects of technological or economic interdependence.

Now, suppose there are m types of fishing effort, each associated with different fishing vessels and gears, and for k = 1,...,m, let E(k,t) denote the fishing effort of type k in operation at time t, and h(i,k,t) denote the harvest of species i (=1,...,n) by fishing effort of type k at time t.

Then by equation (3.41),

$$h(i,k,t) = q(i)d(i,k)E(k,t)B(i,t), \qquad (3.45)$$
$$i=1,\ldots,n \ ; \ k=1,\ldots,m,$$

where d(i,k) is the relative catchability coefficient corresponding to the fishing effort E(k,t) in harvesting species i. The total harvest of species i at time t is

$$h(i,t) = \sum_k h(i,k,t)$$
$$= q(i)\{\sum_k d(i,k)E(k,t)\}B(i,t), \qquad (3.46)$$
$$i=1,\ldots,n$$

and the total harvest by fishing effort E(k,t) at time t is

$$h(-,k,t) = \sum_i h(i,k,t)$$

$$= \{\sum_i q(i)d(i,k)B(i,t)\}E(k,t), \quad (3.47)$$

$$k=1,\ldots,m.$$

Thus the <u>total harvest</u> at time t is

$$h(t) = \sum_k \sum_i q(i)d(i,k)E(k,t)B(i,t). \quad (3.48)$$

To transform the multi-fishing effort to a single equivalent directed fishing effort, we first define

$$E(i,*,t) = [1/d(i,c)] \sum_k d(i,k)E(k,t), \quad (3.49)$$

$$1 \leqslant c \leqslant m \; ; \quad i=1,\ldots,n$$

where E(c,t) is a suitable chosen 'standard' fishing effort. As can be seen, E(i,*,t) is a linear function of all fishing efforts employed in harvesting species i and is regarded as a 'composite' measure of fishing effort at time t. Equation (3.49) thus expresses all the fishing efforts E(k,t) harvesting species i to a 'total single equivalent' fishing effort directed solely at species i. We will refer to it simply as the composite fishing effort directed at species i at time t.

The total harvest of species i (=1,...,n) at time t as given by equation (3.46) can then be written as

$$h(i,t) = q(i)d(i,c)E(i,*,t)B(i,t),$$

or simply as

$$h(i,t) = Q(i)E(i,*,t)B(i,t) \quad (3.50)$$

where $Q(i) = q(i)d(i,c)$ is a constant catchability

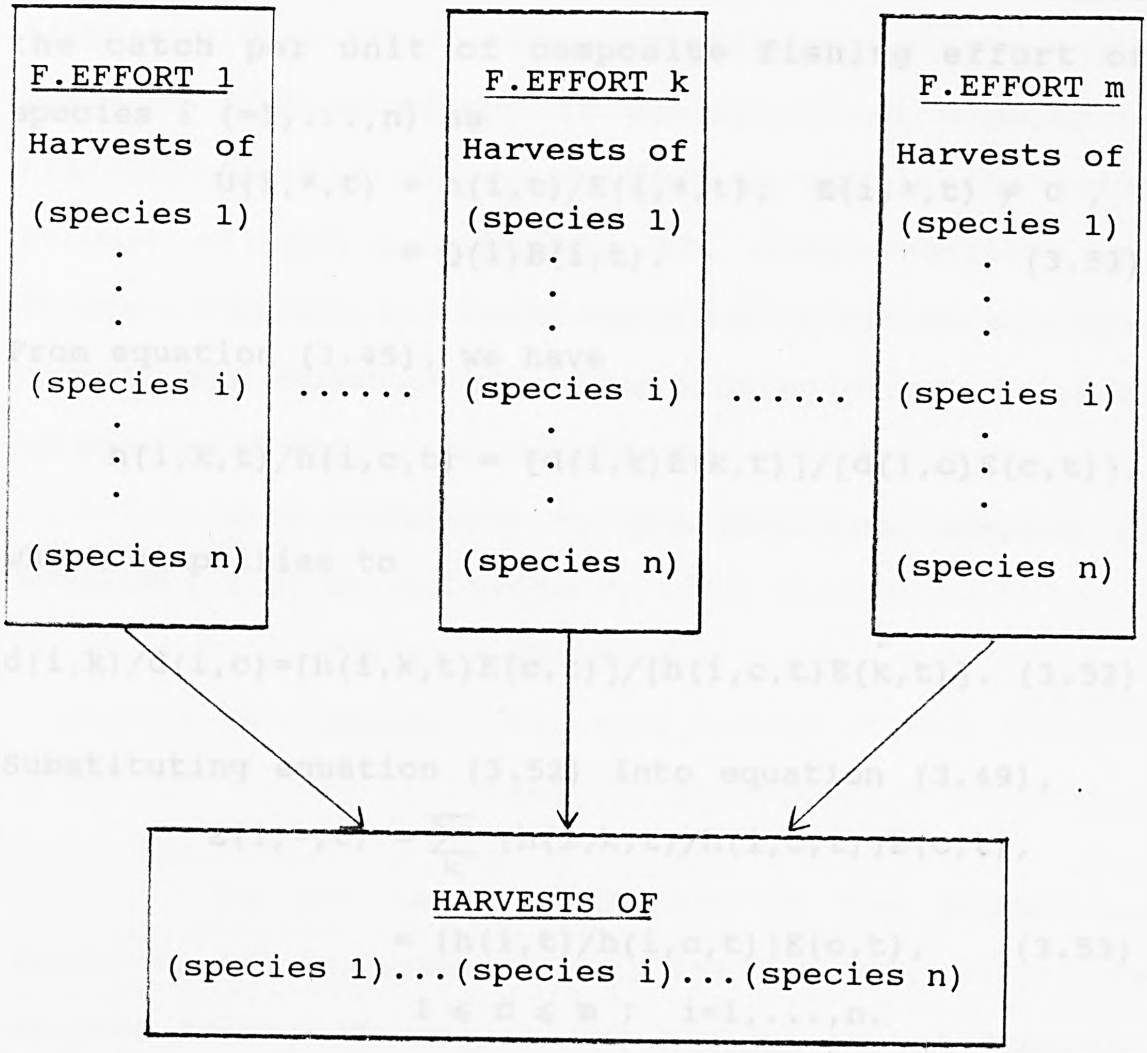


Figure 3.6 Technological or economic interdependence between fishing efforts.

coefficient associated with the harvesting of species i by the single directed composite fishing effort E(i,*,t). Equation (3.50) is the production function associated with the technological interdependence.

Corresponding to E(i,*,t), we can also define the catch per unit of composite fishing effort of species i (=1,...,n) as

$$U(i,*,t) = h(i,t)/E(i,*,t), \quad E(i,*,t) \neq 0 ,$$
$$= Q(i)B(i,t). \qquad (3.51)$$

From equation (3.45), we have

$$h(i,k,t)/h(i,c,t) = [d(i,k)E(k,t)]/[d(i,c)E(c,t)],$$

which simplifies to

$$d(i,k)/d(i,c)=[h(i,k,t)E(c,t)]/[h(i,c,t)E(k,t)]. \qquad (3.52)$$

Substituting equation (3.52) into equation (3.49),

$$E(i,*,t) = \sum_{k} \{h(i,k,t)/h(i,c,t)\}E(c,t),$$
$$= \{h(i,t)/h(i,c,t)\}E(c,t), \qquad (3.53)$$
$$1 \leqslant c \leqslant m \; ; \quad i=1,...,n.$$

Observe that

$$U(i,*,t) = h(i,t)/E(i,*,t)$$
$$= h(i,c,t)/E(c,t)$$
$$= U(i,c,t), \qquad (3.54)$$

which implies that the catch per unit of directed composite fishing effort of species i (=1,...,n) is equal to the catch per unit of the 'standard' fishing effort of species i.

Computation of E(i,*,t)

Equation (3.53) also enables us to compute the directed composite fishing effort E(i,*,t). First, a suitable fishing effort is chosen from the m types of fishing effort in operation to act as a standard fishing effort E(c,t). Each species harvested by this standard fishing effort is estimated and denoted by h(i,c,t) for all i=1,...,n. Next we obtain the total harvest of each species from all fishing efforts and denote it by h(i,t). Using equation (3.53) we can then compute the directed composite fishing effort E(i,*,t) of species i (=1,...,n) at time t.

With reference to the notations adopted in section 3.2.5, we can write

$$E(i,t) = E(i,*,t)$$
$$U(i,t) = U(i,*,t), \qquad (3.55)$$
$$i=1,...,n.$$

So far in our analysis of the production function, the economic output, the harvest, h(i,t) is assumed to depend only on the biological and economic inputs which take the form of the size of the fish stock, B(i,t) and the fishing effort, E(i,t) respectively. Despite its simplicity, it remains the most popular version adopted in fishery studies.

The biological input, the stock of fish is an unobservable quantity. It is not unreasonable to assume that the density of the fish stock varies with the

depth of the fishing ground, and hence with the distance from the fishing port. Thus the choice of fishing location can lead to variations in the harvest. Inclusion of the relationship between the density of the fish stock and location fished, whenever possible and data permitted, in the estimated production function will obviously bring the harvesting model closer to reality.

However, to include this relationship (between density and location fished) is not as simple as it seems. Fishing vessels seldom fish at a single location during any one fishing season but move from locations to locations according to the abundance of the fish. Although fishing trips are normally recorded, for example in the vessel's log book, the fishing locations (and particularly the depths of the fishing spots) are seldom collected and published. Furthermore, the large number of fishing vessels in operation, each making numerous fishing trips to different fishing grounds would make the analysis lengthy and complicated. Thus, until a time when complete informations (and data) on fishing locations are available, we will have to confine the biological input to just a single unobservable quatity, the size of the fish stock assumed homogeneous throughout the fishing ground.

The economic input, the fishing effort adopted in most fishery studies comprises of fishing time and/or vessel's characteristics as well as the

type of fishing gears used. Data on capital and labour are seldom included in fishery statistics despite their importance to the fishing activity. It is thus impossible to check for changes in efficiency (that is the catchability coefficient) over the period of the data employed in the estimation of the production function. Efficiency, and hence the catchability coefficient must therefore be assumed constant over time.

As mentioned earlier, the study looks at two measures of fishing effort — the number of hours spent fishing and the ton-hours fishing. Neither measure is perfect, but they constitute the alternatives for quantitatively defining the economic aspect of fishing activity.

3.3.3 Price Demand Function

Various economics and social factors are generally taken into consideration in determining a demand or price function for a particular good. This includes details such as consumer income, price of competing goods, imports of similar goods, or other variables such as the size and characteristics of the population, inflation, consumer preferance and so on. Most of these determinants are not easily measurable and in general will require a separate study.

But when we speak of price demand function, we normally refer to the mathematical relationship

between the selling price and the quantity of goods in question. This relationship is normally assumed to be of an inverse type such that the selling price of the good varies inversely with the amount available to the market during a specified period. With reference to fishery, this implies that the selling price of fish changes as the fishery expands or contracts its fishing efforts and hence its output, the harvest. However, the total supply of fish in any country not only comprises of the total landings of fish in that country from all the fishing grounds but also includes its imports. This is illustrated in figure 3.7.

The relationship between the unit price, P(t) and the quantity of goods available, S(t) at time t can be written as

$$P(t) = p_o + b'.S(t), \qquad (3.56)$$

where p_o and b′ are positive and negative constants respectively. Equation (3.56) simply represents a downward-sloping curve (figure 3.8). The constant p_o represents the maximum price that the society is willing to pay for a unit of good, whereas the constant b′ refers to the marginal change (decrease) in price for each unit of change (increase) in the quantity of good supplied.

With reference to fishery, equation (3.56) can be written as

$$P(i,t) = p_o(i) + b'(i).S(i,t), \qquad (3.57)$$

$$i = 1,\ldots,n$$

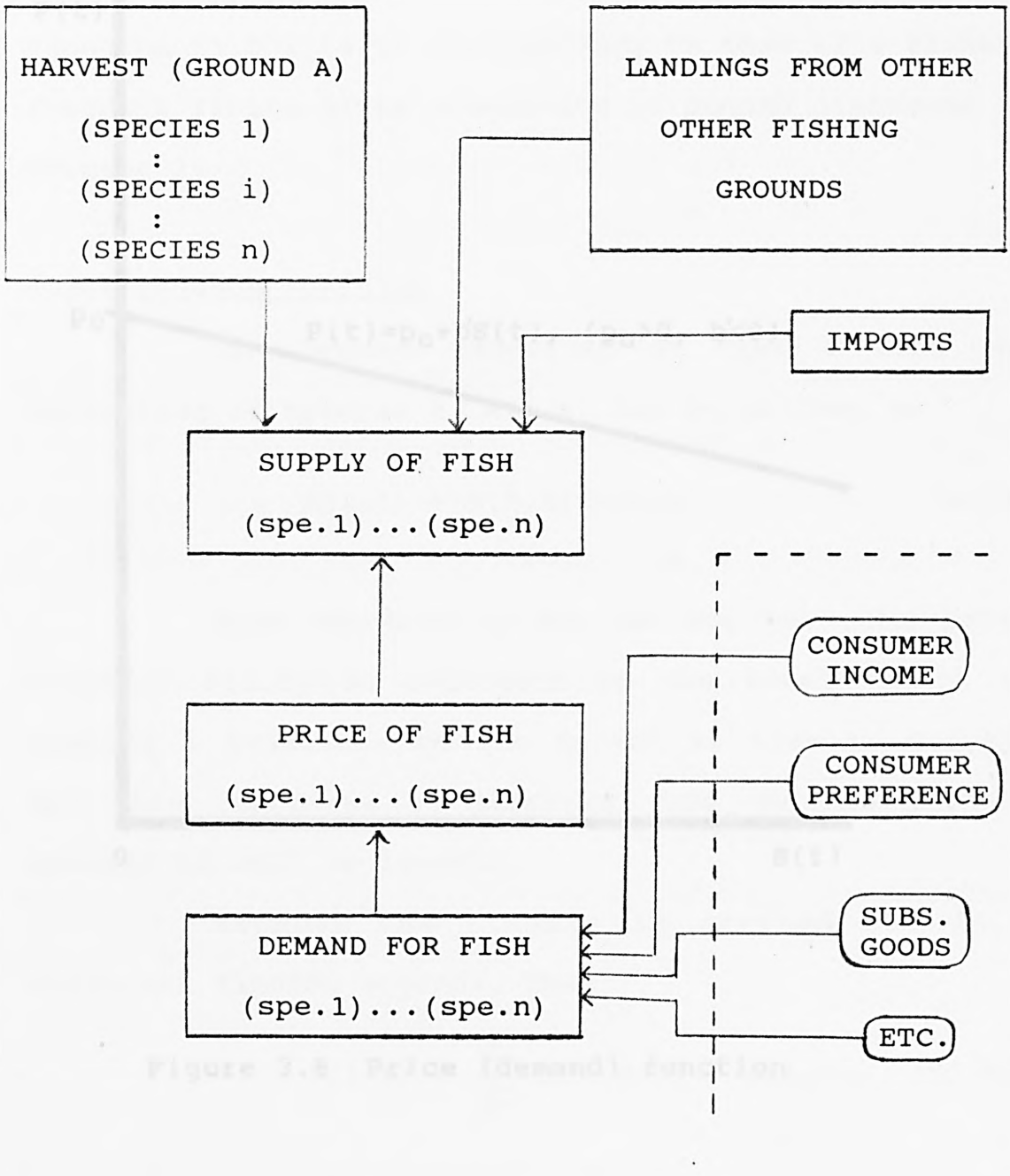


Figure 3.7 Fishery marketing sector

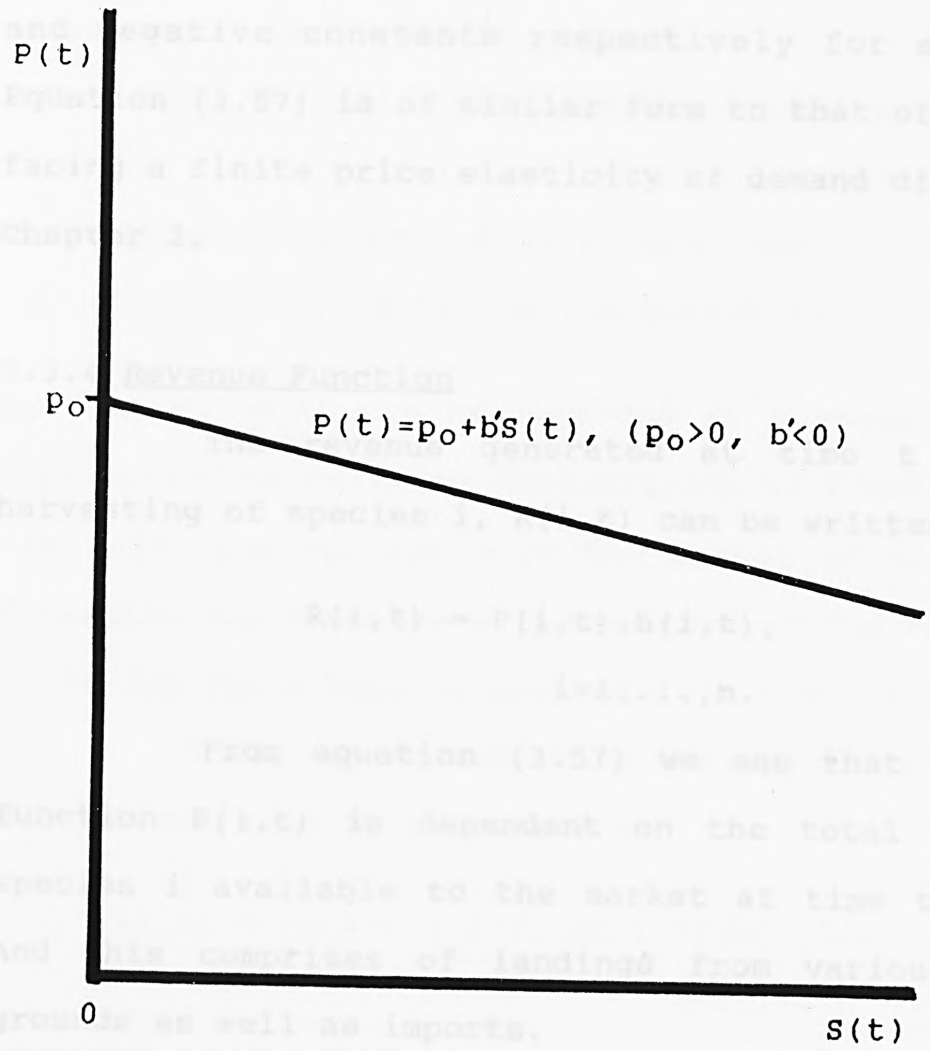


Figure 3.8 Price (demand) function

where P(i,t) is the unit price of species i at time t, S(i,t) is the total supply of species i available to the market at time t, and $p_o(i)$ and b'(i) are positive and negative constants respectively for species i. Equation (3.57) is of similar form to that of a fishery facing a finite price elasticity of demand discussed in Chapter 2.

3.3.4 Revenue Function

The revenue generated at time t from the harvesting of species i, R(i,t) can be written as

$$R(i,t) = P(i,t).h(i,t), \qquad (3.58)$$
$$i=1,\ldots,n.$$

From equation (3.57) we see that the price function P(i,t) is dependent on the total amount of species i available to the market at time t, S(i,t). And this comprises of landings from various fishing grounds as well as imports.

Suppose the fishery is carried out in L different fishing grounds. Then

$$S(i,t) = \sum_{g=1}^{L} h(i,g,t) + I(i,t), \qquad (3.59)$$
$$i=1,\ldots,n$$

where h(i,g,t) is the amount of species i harvested from ground g (=1,...,L) at time t, and I(i,t) is the amount of species i imported at time t.

Since the focus of this study is only on one fishing ground, namely the North Sea, we will want a

revenue function that will relate the revenue generated by each species to the amount or quantity of each species harvested from that fishing ground. To do this, rewrite equation (3.57) as

$$P(i,t) = p_o(i) + [b'(i)/e(i,g,t)]h(i,g,t) \quad (3.60)$$

$$i=1,\ldots,n \ ; \ g=1,\ldots,L$$

where $h(i,g,t)$ is defined as before, and

$$e(i,g,t) = h(i,g,t)/S(i,t). \quad (3.61)$$

The term $e(i,g,t)$ can be regarded as a measure of the contribution or relative productivity of fishing ground g in supplying species i to the market at time t. It represents the fraction or percentage of the total supply of species i that originated from fishing ground g.

Thus, using equation (3.60), the revenue function can then be expressed as

$$R(i,t) = [p_o(i) + b(i,t)h(i,t)]h(i,t), \quad (3.62)$$

$$i=1,\ldots,n$$

where $h(i,t) = h(i,g,t)$ when covering only one fishing ground, g and

$$b(i,t) = b'(i)[S(i,t)/h(i,t)],$$

$$= b'(i)/e(i,g,t), \quad i=1,\ldots,n. \quad (3.63)$$

The total revenue generated in the fishery (from a single fishing ground) at time t is therefore,

$$TR(t) = \sum_i R(i,t),$$

$$= \sum_i [p_o(i) + b(i,t)h(i,t)]h(i,t) \quad (3.64)$$

which is quadratic in $h(i,t)$.

Using equation (3.26), the revenue function can also be alternatively expressed as

$$R(i,t)=[p_o(i)+b(i,t)U(i,t)E(i,t)]U(i,t)E(i,t), \quad i=1,\ldots,n \tag{3.65}$$

where $U(i,t)$ and $E(i,t)$ are the catch per unit of composite fishing effort of species i and the total equivalent composite fishing effort directed at species i respectively. The total revenue generated at time t in this case is thus

$$TR(t) = \sum_i \{[p_o(i)+b(i,t)U(i,t)E(i,t)]U(i,t)E(i,t)\}. \tag{3.66}$$

3.3.5 Cost Function

To complete the economic analysis we also require informations on the cost of economic inputs, namely the fishing effort. A derivation of cost function requires informations on labour, capital, depreciation, interests, operating expenses, etc. However, we are again face with data constraint in our attempt to derive a 'suitable' cost function.

An approximate cost function, however can be estimated from the revenue-effort data or the catch per unit of fishing effort where catch is expressed in value or monetary terms. Total cost is made up of total fixed costs such as capital and total variable costs such as operating expenses. Assuming a linear relationship, we can then write

$$TC(i,t) = C_F(i) + c(i)E(i,t), \qquad (3.67)$$
$$i=1,\ldots,n$$

where $TC(i,t)$ is the total cost incurred in employing a directed composite fishing effort $E(i,t)$, $C_F(i)$ is the associated fixed cost (assumed constant) and $c(i)$, $(i=1,\ldots,n)$ which will be assumed positive and constant is the operating cost per unit of directed composite fishing effort. This relationship is graphed in figure 3.9.

The total cost can thus be written as

$$TC(t) = \sum_i TC(i,t)$$

$$= C_F + \sum_i c(i)E(i,t), \qquad (3.68)$$

where $C_F = \sum_i C_F(i)$ is the total fixed costs.

As in other economic production processes, the fishery in the long run tends to converge to an equilibrium state (namely that of bioeconomic equilibrium discussed in Chapter 2) at which the average revenue equals the average cost. Average cost in most cases is taken to be the average operating cost, that is the unit cost of fishing effort.

And as long as fishing continues for an extended period of time, the revenue generated should be at least greater than the operating cost of fishing. Thus in relation to directed composite fishing effort, the 'value' of the catch per unit of directed composite fishing effort for each species should remain at least as high as the unit cost of directed composite fishing

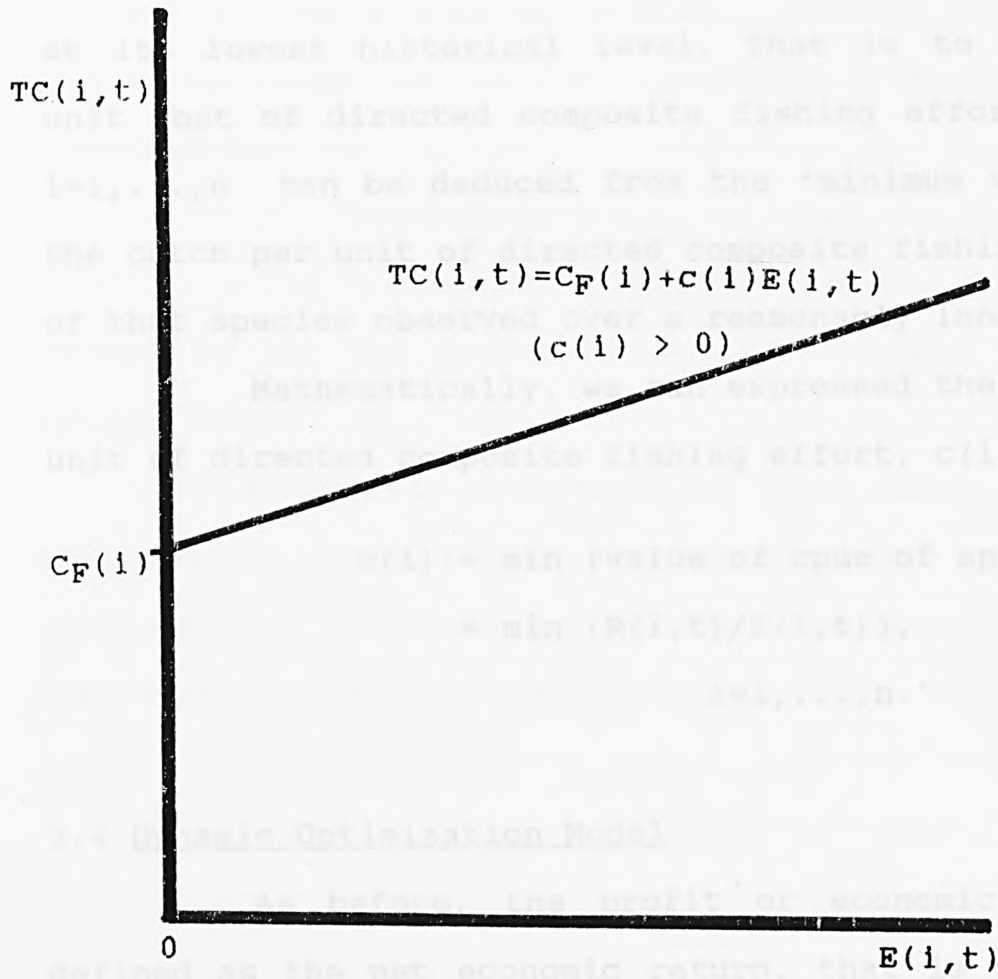


Figure 3.9 Linear cost function

effort. Thus, in the absence of a more reliable information on fishing cost, we can make an approximate estimate of the unit cost from the value of catch per unit of directed composite fishing effort is observed at its lowest historical level. That is to say, the unit cost of directed composite fishing effort, c(i), i=1,...,n can be deduced from the 'minimum value' of the catch per unit of directed composite fishing effort of that species observed over a reasonably long period.

Mathematically, we can expressed the cost per unit of directed composite fishing effort, c(i) as

$$\begin{aligned} c(i) &= \min \{\text{value of cpue of species } i\}, \\ &= \min \{R(i,t)/E(i,t)\}, \qquad (3.69) \\ &\qquad i=1,\ldots,n. \end{aligned}$$

3.4 Dynamic Optimization Model

As before, the profit or economic rent is defined as the net economic return, that is the total revenue generated less the total cost incurred. Using similar notations as before,

$$Z(t) = TR(t) - TC(t) \qquad (3.70)$$

where Z(t) is the total profit generated at time t.

Dynamic optimization in a multispecies model therefore implies the maximization of the present value of the total net return. This can generally be stated as

$$\text{Max.} \int_0^\infty e^{-\theta t} Z(t).dt$$

$$= \text{Max.} \int_0^\infty e^{-\theta t} \{TR(t) - TC(t)\}dt, \qquad (3.71)$$

subject to a set of n constraints describing the changes in the stocks of n fish species as given by equation (3.8) or (3.10), and the non-negativity constraints,

$$0 \leqslant h(i,t) \leqslant h_{max}(i), \; i=1,\ldots,n$$
$$\text{or} \quad 0 \leqslant E(i,t) \leqslant E_{max}(i), \; i=1,\ldots,n \qquad (3.72)$$

depending on the control variable chosen for the optimization.

A formal statement of the above dynamic multispecies optimization problem is taken up in the next chapter where it is reformulated into a multi-dimensional optimal control problem.

CHAPTER 4

DYNAMIC OPTIMIZATION TECHNIQUE

4.1 Statement of the Problem

In Chapter 2 we saw how the optimal control theory was applied to a dynamic single species model. In this chapter, a similar technique but in a multi-dimensional framework is applied to a dynamic multi-species model developed in the previous chapter and solved by the Pontryagin maximum principle.

Let us first restate formally the general optimization problem for the full multispecies model so far developed. The dynamic optimal economic policy is defined earlier (see section 3.4) as that policy which when implemented results in a maximum present value (MPV). The present value of an economic strategy is simply the discounted net value of all future returns, that is the discounted net value of all future profits. Using similar notations as before, the present value of any harvest strategy is thus given by

$$PV = \int_0^\infty e^{-\theta t} Z(\underline{B}(t), \underline{h}(t))\,dt \qquad (4.1)$$

where θ is a constant discount rate,

$$\underline{B}(t) = \begin{bmatrix} B(1,t) \\ \vdots \\ B(n,t) \end{bmatrix} \qquad (4.2)$$

is a stock vector representing a state vector associated with n state variables $B(1,t),\ldots,B(n,t)$,

and

$$\underline{h}(t) = \begin{bmatrix} h(1,t) \\ \vdots \\ h(n,t) \end{bmatrix} \tag{4.3}$$

is a harvest vector representing a control vector associatiated with n control variables $h(1,t),\ldots,h(n,t)$. Throughout the study, the harvest vector is chosen as the control vector simply because of its relatively simpler algebraic formulation as compared to the fishing effort vector $\underline{E}(t)$ which is associated with fishing efforts $E(1,t),\ldots,E(n,t)$.

The dynamics of the state variables are governed by a system of n differential equations

$$dB(i,t)/dt = f_i(B(1,t),\ldots,B(n,t)) - h(i,t) \quad i=1,\ldots,n \tag{4.4}$$

which can be written in a vector form as

$$d\underline{B}(t)/dt = \underline{f}(\underline{B}(t)) - \underline{h}(t) \tag{4.5}$$

where

$$\underline{f}(\underline{B}(t)) = \begin{bmatrix} f_1(B(1,t),\ldots,B(n,t)) \\ \vdots \\ f_n(B(1,t),\ldots,B(n,t)) \end{bmatrix}. \tag{4.6}$$

The state and control vectors are normally assumed to be nonnegative and bounded, thus imposing constraints of the form

$$0 \leqslant B(i,t) \leqslant B_{max}(i), \tag{4.7}$$

and

$$0 \leqslant h(i,t) \leqslant h_{max}(i)$$

for all $i=1,\ldots,n$. Furthermore, we will assume that the initial values of these variables $\underline{B}(0)$ and $\underline{h}(0)$ are

also known or can be estimated.

The optimization involved is then that of finding the best functions h(i,t), i=1,...,n such that these functions and the corresponding solutions B(i,t), i=1,...,n maximise the objective functional PV as given by the integral in equation (4.1). This determination of time path for the optimal harvest or control vector $\underline{h}(t)$ is a problem in optimal control theory solvable by the method of maximum principle.

4.2 Optimal Control Theory: The Maximum Principle

To formulate the maximum principle, we define the Hamiltonian

$$H(\underline{B}(t),\underline{h}(t),t,\underline{L}(t)) = e^{-\theta t}Z(\underline{B}(t),\underline{h}(t)) + \underline{L}(t).[\underline{f}(\underline{B}(t)) - \underline{h}(t)] \quad (4.8)$$

where

$$\underline{L}(t) = \begin{bmatrix} L(1,t) \\ \cdot \\ \cdot \\ \cdot \\ L(n,t) \end{bmatrix} \quad (4.9)$$

is a vector of Lagrange multipliers whose components L(i,t), i=1,...,n are usually referred to as the adjoint or co-state variables. The second term on the right side of equation (4.8) is the usual dot product of two vectors $\underline{L}(t)$ and $\underline{f}(B(t)) - \underline{h}(t)$.

Assuming that the control problem defined by equations (4.1) to (4.7) possesses an optimal solution $\underline{h}(t)$ with response $\underline{B}(t)$, the optimal harvest $\underline{h}(t)$ then maximizes the Hamiltonian at every time subject to a

number of necessary conditions. The maximum principle in general asserts three necessary conditions on $\underline{B}(t)$, $\underline{h}(t)$ and $\underline{L}(t)$:

(1) The adjoint (or co-state) equations

The adjoint variables must satisfy the adjoint equations

$$d\underline{L}(t)/dt = - \partial H/\partial \underline{B}(t) \tag{4.10}$$

where

$$\partial H/\partial \underline{B}(t) = \begin{bmatrix} \partial H/\partial B(1,t) \\ \vdots \\ \partial H/\partial B(n,t) \end{bmatrix} \tag{4.11}$$

In scalar form, this implies that

$$dL(i,t)/dt = -e^{-\theta t}(\partial Z/\partial B(i,t)) - \sum_j L(j,t)\{\partial f_j(\underline{B}(t))/\partial B(i,t)\} \tag{4.12}$$

$$i=1,\ldots,n.$$

(2) The state equations

The state variables must satisfy the state equations (also known as the equations of motion),

$$d\underline{B}(t)/dt = \partial H/\partial \underline{L}(t) \tag{4.13}$$

where

$$\partial H/\partial \underline{L}(t) = \begin{bmatrix} \partial H/\partial L(1,t) \\ \vdots \\ \partial H/\partial L(n,t) \end{bmatrix} . \tag{4.14}$$

Transforming to scalar form, equation (4.13) implies

$$dB(i,t)/dt = f_i(\underline{B}(t)) - h(i,t), \tag{4.15}$$

$$i=1,\ldots,n$$

which corresponds to a set of n differential equations describing the dynamics of the state variables as

previously defined by equations (4.4) and (4.5).

(3) The maximum principle

Since the optimal harvest $\underline{h}(t)$ maximizes the Hamiltonian, we must then have

$$\partial H/\partial \underline{h}(t) = \underline{0} \qquad (4.16)$$

for all $t \geqslant 0$, where

$$\partial H/\partial \underline{h}(t) = \begin{bmatrix} \partial H/\partial h(1,t) \\ \vdots \\ \partial H/\partial h(n,t) \end{bmatrix} . \qquad (4.17)$$

In scalar form, this implies that

$$e^{-\theta t}\{\partial Z/\partial h(i,t)\} = L(i,t), \quad i=1,\ldots,n. \qquad (4.18)$$

Equations (4.12), (4.15) and (4.18) or the corresponding vector equations (4.10), (4.13) and (4.16) constitute a system of 2n nonlinear first order ordinary differential equations and n nonlinear algebraic equations in 3n unknowns B(i,t), h(i,t) and L(i,t), i=1,...,n. Thus in principle the optimal strategy associated with the optimal harvest and stock can be determined by solving these set of equations.

In finite time horizon problems where a terminal condition is imposed on the state variable $\underline{B}(t)$ such that

$$B(i,T) = B_T(i), \quad i = 1,\ldots,n, \qquad (4.19)$$

the feasible control $\underline{h}(t)$ is defined to be any admissable control such that the response satisfies this terminal condition as well as the (assumed known) initial condition $\underline{B}(0)$. The optimal time paths in this

case is thus determined by solving a <u>two-point boundary value problem</u> specified by the state and the co-state equations $d\underline{B}(t)/dt$ and $d\underline{L}(t)/dt$ such that the initial and terminal conditions on the state variables, $\underline{B}(0)$ and $\underline{B}(T)$ are both satisfied.

However, in certain finite time horizon problems where no terminal condition is specified on the state variable (problems normally referred to as free terminal-value problems), the maximum principle is extended by adding a <u>transversality condition</u> on the co-state variable $\underline{L}(t)$ such that

$$L(i,T) = 0, \quad i = 1,\ldots,n \qquad (4.20)$$

where T ($< \infty$) is the terminal time.

With reference to equation (4.18), for finite T, this suggests that

$$\partial Z/\partial h(i,t)\Big|_{t=T} = 0, \quad i = 1,\ldots,n \qquad (4.21)$$

since $e^{-\theta t} \neq 0$ for $t = T < \infty$.

Now, $\partial Z/\partial \underline{h} = \underline{0}$ is a necessary condition for maximum economic profit. Equation (4.21) therefore suggests that for a finite time horizon, the harvest rate in the terminal period (t=T) should be such that the economic profit in that period is maximised regardless of the performances in other previous periods. The optimal time paths in this case still involve solving the two-point boundary value problem but with the terminal state condition replaced by the transversality condition $\underline{L}(T) = \underline{0}$.

Getz and Haight (1989 : p100) suggested that in certain cases the problem of specifying the transversality condition on $\underline{L}(T)$ can be avoided by allowing $T \rightarrow \infty$. Now, in this case of an infinite time horizon, $T \rightarrow \infty$ (as considered in the study), equation (4.18) gives

$$L(i,T)\Big|_{T \rightarrow \infty} = 0, \quad i = 1,\ldots,n \qquad (4.22)$$

since $e^{-\theta T}\Big|_{T \rightarrow \infty} = 0,$

regardless of the expression $\partial Z/\partial \underline{h}\Big|_{T \rightarrow \infty}$.

However, it is much desired that it is the expression $\partial Z/\partial \underline{h}(T)$ that should approach zero first rather than $e^{-\theta T}$ as $T \rightarrow \infty$, that is

$$\partial Z/\partial \underline{h}(t)\Big|_{T \rightarrow \infty} = \underline{0}. \qquad (4.23)$$

In view of the difficulties usually encountered in solving a two-point boundary value problem in an infinite time horizon, it might be preferable to seek a near optimal or suboptimal solution by relaxing the transversality condition on $\underline{L}(T)$ as $T \rightarrow \infty$. This enables us to reduce the 3n equations to a system of 2n nonlinear first order ordinary differential equations which can be solved by numerical methods.

At this point, it should be stressed that solutions obtained by solving the reduced system of 2n nonlinear ordinary differential equations should not be regarded as true optimal solutions. At best, they are only suboptimal solutions.

Now, differentiating equation (4.18) with respect to time t, we obtain

$$dL(i,t)/dt = -\theta e^{-\theta t}\{\partial Z/\partial h(i,t)\} + e^{-\theta t}\sum_j \{[\partial^2 Z/\partial h(i,t)\partial h(j,t)][dh(j,t)/dt] + [\partial^2 Z/\partial h(i,t)\partial B(j,t)][dB(j,t)/dt]\}, \quad i=1,\ldots,n \tag{4.24}$$

Equating equation (4.24) with the adjoint equation (4.12) and using equation (4.18) and the state equation (4.15), we obtain (dropping the suffix t for simplicity)

$$-e^{-\theta t}\{\partial Z/\partial B(i)\} - \sum_j e^{-\theta t}\{\partial Z/\partial h(j)\}\{\partial f_j(\underline{B})/\partial B(i)\} = -\theta\, e^{-\theta t}\{\partial Z/\partial h(i)\} + e^{-\theta t}\sum_j \{[\partial^2 Z/\partial h(i)\partial h(j)][dh(j)/dt] + [\partial^2 Z/\partial h(i)\partial B(j)][f_j(\underline{B}) - h(j)]\}$$

which simplifies to

$$\sum_j \{[\partial^2 Z/\partial h(i)\partial h(j)][dh(j)/dt] + [\partial^2 Z/\partial B(j)\partial h(i)][f_j(\underline{B}) - h(j)]\} = \theta[\partial Z/\partial h(i)] - \partial Z/\partial B(i) - \sum_j [\partial Z/\partial h(j)][\partial f_j(\underline{B})/\partial B(i)], \quad i=1,\ldots,n. \tag{4.25}$$

Although $\underline{h}(t)$ (or $d\underline{h}/dt$) as expressed by equations (4.25) is rather complex, it nevertheless reduces the total number of equations to be solved from 3n to just 2n associated with only the state and the control variables.

Also, since we are assuming that the initial conditions $\underline{B}(0)$ and $\underline{h}(0)$ are known, the problem then reduces to that of an initial boundary value problem involving 2n (nonlinear) first order ordinary differential equations in 2n unknowns.

4.3 Economic Interpretations

Before we apply the optimal control theory presented in the last section to the dynamic multi-species fishery model, we will attempt to give a brief economic interpretation to some of the terms and expressions encountered in the derivation of the dynamic optimal strategy.

In economic analysis, the adjoint variable L(i) is usually referred to as the 'shadow price' of the ith capital stock B(i). It reflects the 'marginal value' of the capital stock such that if the stock level is changed by one unit at time t, its value will be changed by L(i,t). From equation (4.18) we see that L(i,t) is simply the discounted marginal value of the future profit since $\partial Z/\partial h(i)$ is the marginal profit from the sale of an additional unit of harvest.

The Hamiltonian defined by equation (4.8) comprises of two terms. The first, $e^{-\theta t}Z(\underline{B}(t),\underline{h}(t))$ is the value of the flow of the total accumulated 'dividends' (Clark, 1976) to the objective functional PV, or just simply the value of the total accumulated discounted profit. The second term, on the other hand,

is the sum of the products of the shadow price L(i,t) and the rate of change of the ith stock, dB(i,t)/dt. Now,

$$dB(i,t)/dt = f_i(\underline{B}(t),t) - h(i,t), \quad i=1,\ldots,n$$

reflects the flow of 'investment' in the ith capital, that is the change in the ith capital stock. Multiplication by its shadow price expresses this investment flow in its value terms. Thus the Hamiltonian which is the sum of these two flows (of dividends and investments) is normally regarded as the total rate of change of the total assets.

It should be noted that in some literatures, the discounted shadow price L(i,t) is sometimes replaced by the current shadow price u(i,t), such that

$$u(i,t) = e^{\theta t}L(i,t),$$

and the Hamiltonian by the current-value Hamiltonian H^ such that

$$\begin{aligned} H^{\wedge} &= e^{\theta t}H(\underline{B},\underline{h},t,\underline{L}) \\ &= Z(\underline{B},\underline{h}) + \underline{u}(t).[\underline{f}(\underline{B}) - \underline{h}) \end{aligned} \tag{4.26}$$

where

$$\underline{u}(t) = \begin{bmatrix} u(1,t) \\ \vdots \\ u(n,t) \end{bmatrix}. \tag{4.27}$$

The corresponding adjoint equation becomes

$$d\underline{u}(t)/dt = \theta\underline{u}(t) - \partial H^{\wedge}/\partial\underline{B}(t), \tag{4.28}$$

where

$$\partial H^{\wedge}/\partial \underline{B}(t) = \begin{bmatrix} \partial H^{\wedge}/\partial B(1,t) \\ \vdots \\ \partial H^{\wedge}/\partial B(n,t) \end{bmatrix}, \qquad (4.29)$$

and since

$$d\underline{L}(t)/dt = (d/dt)\{e^{-\theta t}\underline{u}(t)\}$$
$$= e^{-\theta t}\{d\underline{u}(t)/dt - \theta \underline{u}(t)\}. \qquad (4.30)$$

4.4 Numerical Computation of Suboptimal Solutions

As can be observed, the dynamic optimization revolves around two main functions, namely the profit $Z(\underline{B}(t),\underline{h}(t))$ and the stock (or population) growth function, $\underline{f}(\underline{B}(t))$.

Recall from equation (3.70) of the previous chapter that the total profit generated at time t is given by

$$Z(\underline{B}(t),\underline{h}(t)) = TR(t) - TC(t)$$

$$= \sum_i \{[p_o(i) + b(i,t)h(i,t)]h(i,t) - c(i)h(i,t)/[Q(i)B(i,t)]\} - C_F \qquad (4.31)$$

where $h(i,t) = Q(i)E(i,t)B(i,t)$, $i=1,\ldots,n$. (4.32)

If we define

$$w_i(B(i,t)) = c(i)/[Q(i)B(i,t)], \quad i=1,\ldots,n, \qquad (4.33)$$

as the cost per unit of harvest of species i (=1,..,n) at time t, equation (4.31) then simplifies to

$$Z(\underline{B}(t),\underline{h}(t)) = \sum_i \{[p_o(i) - w_i(B(i,t))]h(i,t) + b(i,t)[h(i,t)]^2\} - C_F. \qquad (4.34)$$

Also, the dynamics of the fish species are governed by a system of n differential equations as given by equation (3.8),

$$dB(i,t)/dt = r(i)B(i,t)\{1 - B(i,t)/K(i)\} + \sum_{j\neq i} a(i,j)B(i,t)B(j,t) - h(i,t), \quad i=1,\ldots,n \tag{4.35}$$

or equivalently,

$$dB(i,t)/dt = \{a(i,0) + \sum_{j} a(i,j)B(j,t)\}B(i,t) - h(i,t), \quad i=1,\ldots,n \tag{4.36}$$

where

$$\left.\begin{aligned} a(i,0) &= r(i) \\ a(i,i) &= - r(i)/K(i). \end{aligned}\right\} \tag{4.37}$$

Thus

$$f_i(\underline{B}(t)) = \{a(i,0) + \sum_{j} a(i,j)B(j,t)\}B(i,t), \quad i=1,\ldots,n. \tag{4.38}$$

Now, performing various partial differentiations on $Z(\underline{B}(t),\underline{h}(t))$ yield

$$\partial Z/\partial h(i) = p_o(i) - w_i(B(i,t)) + 2b(i,t)h(i,t), \tag{4.39}$$

$$\partial^2 Z/\partial h(i)\partial h(j) = \begin{cases} 2b(i,t), & i=j \\ 0, & i\neq j \end{cases} \tag{4.40}$$

$$\partial Z/\partial B(i) = -\{\partial w_i(B(i,t))/\partial B(i)\}h(i,t) = c(i)h(i,t)/[Q(i)(B(i,t))^2] \tag{4.41}$$

and

$$\partial^2 Z/\partial B(j)\partial h(i) = \begin{cases} c(i)/\{Q(i)[B(i,t)]^2\}, & i=j \\ 0 \quad i\neq j\ . \end{cases} \tag{4.42}$$

Similarly, performing partial differentiation on $f_j(\underline{B}(t))$ with respect to B(i) yields

$$\partial f_j(\underline{B}(t))/\partial B(i) = \begin{cases} a(i,0) + \sum_j a(i,j)B(j,t) \\ \qquad +a(i,i)B(i,t), \quad i=j \\ a(j,i)B(j,t), \quad i\neq j \end{cases} \tag{4.43}$$

Substitution of all the above partial derivatives into equation (4.25) yields (dropping the suffix t for simplicity)

$$\begin{aligned} &2b(i)\{dh(i)/dt\} + c(i)\{f_i(\underline{B})-h(i)\}/\{Q(i)[B(i)]^2\} \\ &\quad = \theta\{p_o(i) - w_i(B(i)) + 2b(i)h(i)\} \\ &\qquad - \sum_{j\neq i}\{p_o(j)-w_j(B(j))+2b(j)h(j)\}a(j,i)B(j) \\ &\qquad - \{p_o(i) - w_i(B(i)) + 2b(i)h(i)\}\{a(i,0) \\ &\qquad\qquad + \sum_j a(i,j)B(j) + a(i,i)B(i)\} \\ &\qquad - c(i)h(i)/\{Q(i)[B(i)]^2\}, \end{aligned}$$

which simplifies to

$$\begin{aligned} &2b(i)\ dh(i)/dt \\ &\quad = \{\theta - a(i,0) - \sum_j a(i,j)B(j) - a(i,i)B(i)\}\{p_o(i) \\ &\qquad + 2b(i)h(i) - c(i)/[Q(i)B(i)]\} \\ &\qquad - \sum_{j\neq i} a(j,i)\{p_o(j) + 2b(j)h(j) \\ &\qquad\qquad - c(j)/[Q(j)B(j)]\}B(j) \\ &\qquad - c(i)f_i(\underline{B})/\{Q(i)[B(i)]^2\}, \end{aligned} \tag{4.44}$$

$$i=1,\ldots,n.$$

Thus the suboptimal policy for the multi-species fishery model is that policy whose state variables B(i,t) and the control variables h(i,t) are solutions of the state equation (4.36) and the control

equation (4.44). These 2n nonlinear ordinary differential equations can be written as

$$dB(i,t)/dt = \{a(i,0) + \sum_j a(i,j)B(j,t)\}B(i,t) - h(i,t), \quad i=1,\ldots,n \quad (4.45)$$

and

$$\begin{aligned} 2b(i)[dh(i,t)/dt] = \{\theta - a(i,0) - \sum_j a(i,j)B(j,t) \\ - a(i,i)B(i,t)\}A(i,t) \\ - \sum_{j\neq i} a(j,i)A(j,t)B(j,t) \\ - \{c(i)/[Q(i)B(i,t)]\}\{a(i,0) \\ + \sum_j a(i,j)B(j,t)\}, \quad (4.46) \\ i=1,\ldots,n \end{aligned}$$

where

$$A(i,t) = p_o(i) + 2b(i)h(i,t) - c(i)/[Q(i)B(i,t)\}.$$

Due to its nonlinear form, an analytical solution for the above system of equations might not be possible. However, if an initial policy such as an initial stock size and harvest for all the species are known or can be estimated, the suboptimal paths for both the stock size and the harvest can be numerically determined by solving the above initial boundary-value problem. This is illustrated in Chapter 6 with reference to the North Sea multispecies fishery.

Once the optimal or suboptimal stock and harvest levels are determined, the corresponding fishing activity, that is the fishing effort level can be computed from the harvest production function

$$h(i,t) = Q(i)B(i,t)E(i,t), \quad i=1,\ldots,n. \quad (4.47)$$

4.5 Initial Boundary-Value Problem : Runge-Kutta Method

Consider an initial boundary-value problem

$$d\underline{X}(t)/dt = \underline{F}(\underline{X}(t),t), \qquad (4.48)$$

$$\underline{X}(t_o) = \underline{X}_o$$

where

$$\underline{X}(t) = \begin{bmatrix} X(1,t) \\ \cdot \\ \cdot \\ X(n,t) \\ X(n+1,t) \\ \cdot \\ \cdot \\ X(2n,t) \end{bmatrix} \qquad (4.49)$$

is a 2n-dimensional vector representing n state variables and n control variables such that

$$\begin{aligned} X(i,t) &= B(i,t) \\ X(n+i,t) &= h(i,t) \qquad i = 1,..,n, \end{aligned} \qquad (4.50)$$

$$\underline{F}(\underline{X}(t),t) = \begin{bmatrix} F_1(\underline{X},t) \\ \cdot \\ \cdot \\ F_n(\underline{X},t) \\ F_{n+1}(\underline{X},t) \\ \cdot \\ \cdot \\ F_{2n}(\underline{X},t) \end{bmatrix} \qquad (4.51)$$

is a 2n-dimensional vector associated with the state and control equations such that

$$\begin{aligned} F_i(\underline{X}(t),t) &= dB(i,t)/dt \\ F_{n+i}(\underline{X}(t),t) &= dh(i,t)/dt \qquad i=1,..,n \end{aligned} \qquad (4.52)$$

and $\underline{X}(t_o) = \underline{X}_o$ is the value of the state and control variables at some initial time t_o such that

$$\begin{aligned} X_i(t_o) &= B(i,t_o) \\ X_{n+i}(t_o) &= h(i,t_o) \qquad i = 1,..,n. \end{aligned} \qquad (4.53)$$

To apply the standard Runge-Kutta method to a system of first order ordinary differential equations, we first choose a step-size, s and define a set of parameters D1(i), D2(i), D3(i) and D4(i) corresponding to the functions $F_i(\underline{X}(t),t)$, i = 1,..,2n such that

$$D1(i) = F_i(X(1,t),..,X(i,t),..,X(2n,t);t),$$

$$D2(i) = F_i(X(1,t)+0.5sD1(1),..,X(i,t)+0.5sD1(i),..,X(2n,t)+0.5sD1(2n); t+0.5s),$$

$$D3(i) = F_i(X(1,t)+0.5sD2(1),..,X(i,t)+0.5sD2(i),..,X(2n,t)+0.5sD2(2n); t+0.5s),$$

$$D4(i) = F_i(X(1,t)+sD3(1),..,X(i,t)+sD3(i),..,X(2n,t)+sD3(2n); t+s) ;$$

$$i = 1,..,2n. \qquad (4.54)$$

The Runge-Kutta method advances the solution for $\underline{X}(t)$ to $\underline{X}(t+s)$ by the approximations

$$X(i,t+s) = X(i,t) + s\{D1(i)+2.D2(i)+2.D3(i)+D4(i)\}/6,$$

$$i = 1,..,2n. \qquad (4.55)$$

Thus, given the initial conditions (4.53), values of X(i,t), i = 1,..,2n (or equivalently B(i,t) and h(i,t), i = 1,..,n) at successive intervals t_o, t_o+s, t_o+2s,... can then be estimated. In cases where the state and/or control variables are also required to satisfy certain constraints, an additional step needs to be included after each iteration before proceeding to the next iteration. The values of X(i,t), i=1,..,2n approximated from equation (4.55) during each iteration

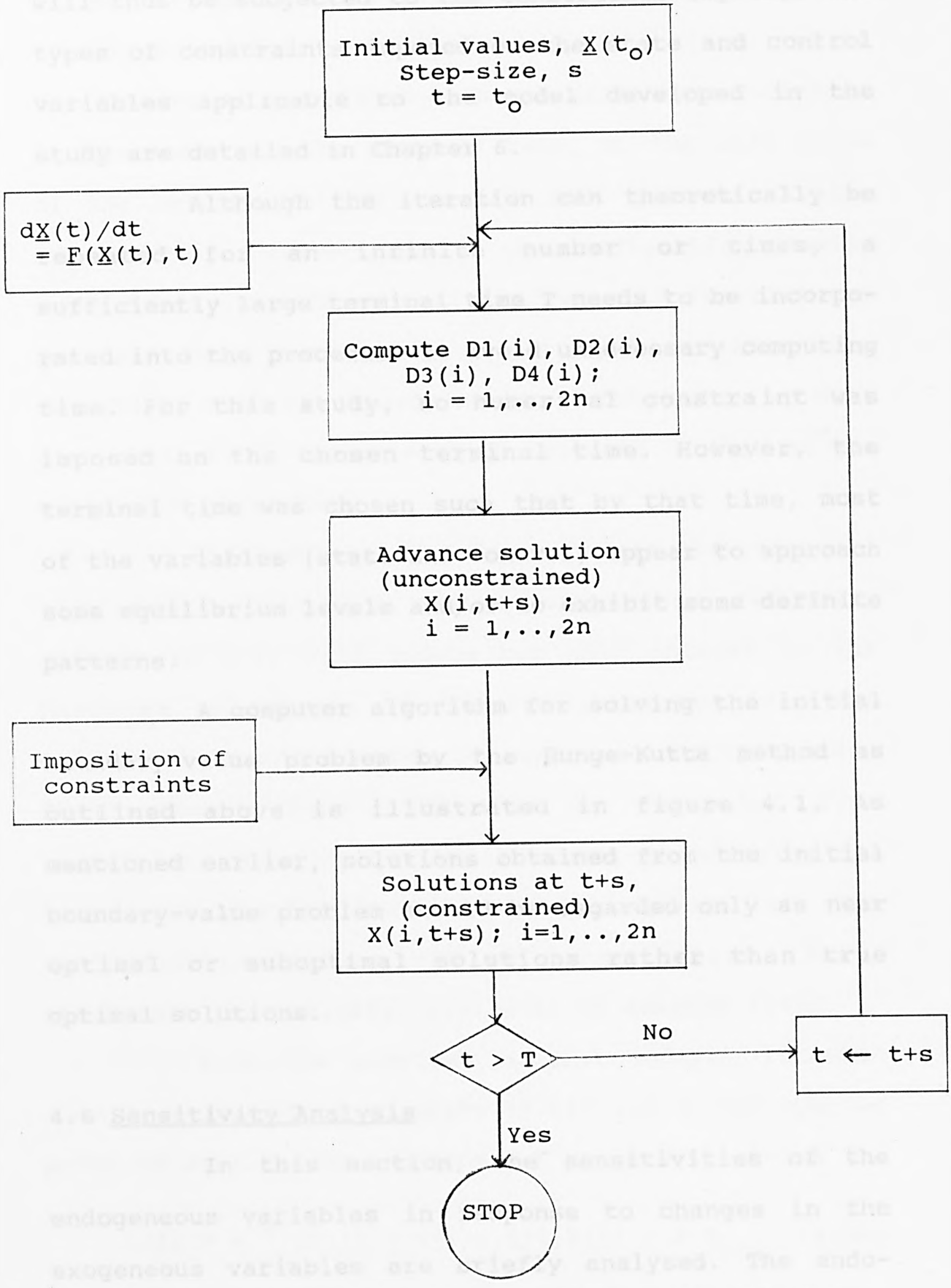


Figure 4.1 An algorithm for Runge-Kutta method

will thus be subjected to the constraints imposed. The types of constraints imposed on the state and control variables applicable to the model developed in the study are detailed in Chapter 6.

Although the iteration can theoretically be repeated for an infinite number or times, a sufficiently large terminal time T needs to be incorporated into the procedure to avoid unnecessary computing time. For this study, no numerical constraint was imposed on the chosen terminal time. However, the terminal time was chosen such that by that time, most of the variables (state and control) appear to approach some equilibrium levels and/or to exhibit some definite patterns.

A computer algorithm for solving the initial boundary-value problem by the Runge-Kutta method as outlined above is illustrated in figure 4.1. As mentioned earlier, solutions obtained from the initial boundary-value problem should be regarded only as near optimal or suboptimal solutions rather than true optimal solutions.

4.6 Sensitivity Analysis

In this section, the sensitivities of the endogeneous variables in response to changes in the exogeneous variables are briefly analysed. The endogeneous variables comprise of the shadow price or the marginal value of the stock, L(i,t), the harvest,

h(i,t), or equivalently the fishing effort, E(i,t), and the stock level or size of the resource, B(i,t), while the parameters associated with the exogeneous variables in the model are the discount rate, θ, the unit price of the harvest, P(i,t) and the unit cost of fishing effort, c(i). However, due to the difficulties usually encountered in such an analysis, we will restrict our analysis to a two species model, and consider only deviations from the steady state. Furthermore, we will also confine the analysis to an increase in each of the exogeneous parameter.

Although one can also consider the catchability coefficient Q(i) as an exogeneous variable, changes in Q(i) will induce not only changes in the harvests and stocks of the resources but also the estimated coefficients of species interactions. Furthermore, since Q(i) will be estimated from regression, changing Q(i) will amount to changing the regression results. And when this happens, all the estimated parameters are no longer valid. Thus, throughout the analysis, Q(i) will be assumed fixed.

From the previous optimal control formulation , we have from equation (4.18) for a two species model in equilibrium and constant price P(i), i=1,2

$$L(i) = e^{-\theta t}\{P(i) - c(i)/[Q(i)B(i)]\} \geq 0, \qquad (4.56)$$

since $$P(i) \geq c(i)/[Q(i)B(i)] = w_i(B(i)), \qquad (4.57)$$

for the fishery to be profitable.

Now, differentiating equation (4.56) with respect to each exogeneous variable gives

$$\partial L(i)/\partial\theta = -\theta.L(i) < 0, \quad i=1,2; \qquad (4.58)$$

$$\partial L(i)/\partial P(i) = e^{-\theta t} > 0, \quad i=1,2; \qquad (4.59)$$

and $$\partial L(i)/\partial c(i) = - e^{-\theta t}/[Q(i)B(i)] < 0, \quad i=1,2; \qquad (4.60)$$

or equivalently

$$\partial L(i)/\partial w_i(B(i)) = - e^{-\theta t} < 0, \quad i=1,2. \qquad (4.61)$$

Equations (4.58) to (4.61) enable us to determine the sensitivity of the shadow price in response to changes in each of the exogeneous variable. From these responses, the sensitivities of the other endogeneous variables can be induced intuitively for each type of species interaction.

4.6.1 <u>The Independent Case</u>

This corresponds to the case where there exist no biological interaction between two species coexisting together in the same ecosystem at the same time. Any change experienced by one species will have no effect whatsoever on the other species. In other words, the impact of a change in the stock of one species on the stock of the other, that is the cross-stock effect, is always zero.

Since the derivatives of both shadow prices with respect to the discount rate are negative, an increase in the discount rate implies a decrease in the

shadow prices of both stocks, that is the value of the unharvested stocks. Economists normally associate this situation with a shifting of consumption patterns from the future to the present. Thus it becomes more profitable to harvest both stocks now rather than later. Fishing efforts directed at both species should then be increased, and followed by an expected increase in the harvests of both species. As a result, the stock levels of both species decline.

An increase in the unit price of one species, say species 1, increases its shadow price and hence the value of its unharvested stock. This can be verified by equation (4.59) for i=1. However, a price increase also tends to induce (at least in the short run) the fishermen to respond by expanding fishing efforts directed at species 1, thereby increasing the harvest of species 1. This results in a decline in the stock level of species 1, B(1). All variables associated with the second species should remain unchanged.

Similarly, an increase in the unit price of the second species, P(2) should affect those variables specific to species 2, with variables specific to species 1 unchanged — an increase in the shadow price of species 2, the shadow price of species 1 unchanged; an increase in the fishing efforts directed at species 2 and hence the harvest of species 2 while fishing efforts and harvest of species 1 remain unchanged; and a decrease in the stock of species 2 with the stock of

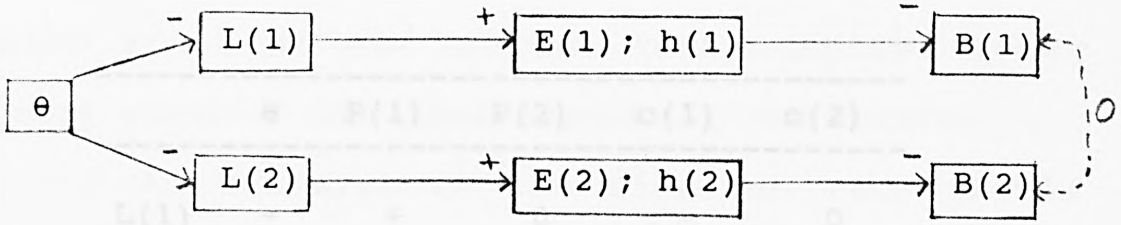
species 1 unchanged.

An increase in the unit cost of harvesting of species 1 has an opposite effect to an increase in the unit price of species 1. Its shadow price decreases, signifying the decline in the value of its unharvested stock, while the value of the unharvested stock of species 2 remains unchanged. Harvesting of species 1 now is more costly, and so fishing efforts directed at it should be reduced, thus decreasing the harvest. This leads to an increase in its steady state stock.

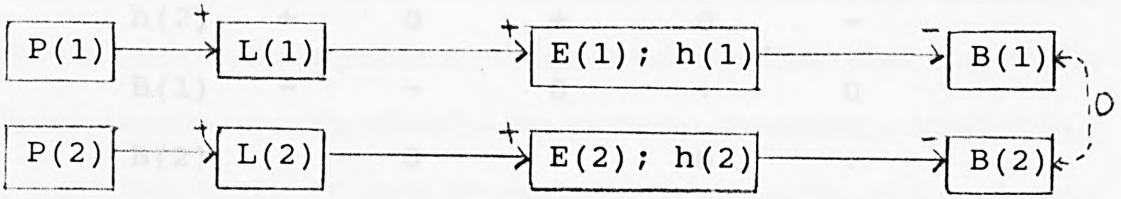
Similarly, an increase in the unit cost of harvesting of species 2 reduces the value of its unharvested stock and so we would expect a decline in the fishing efforts directed at it, resulting in a decreased harvest and thus an increase in its steady state stock. The endogeneous variables associated with species 1 should remain unchanged.

All the above responses can be illustrated by a sign diagram as in figure 4.2 where the -ve and +ve signs signify a decrease and an increase in the corresponding endogeneous variables respectively. Table 4.1 summarises the sensitivities expected from two biologically independent species. Zero signifies no effect associated with the increase in the corresponding exogeneous variable.

(a) Increase in θ



(b) Increase in P(i)



(c) Increase in c(i)

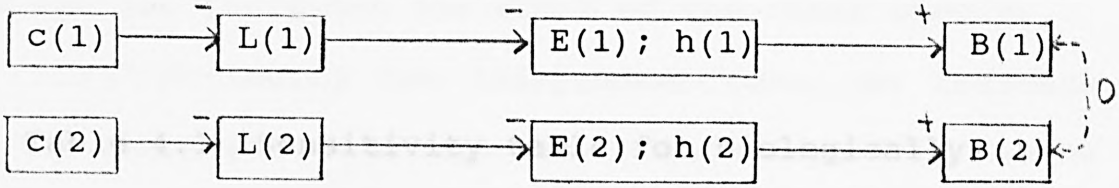


Figure 4.2 Responses in the independent case

	θ	P(1)	P(2)	c(1)	c(2)
L(1)	-	+	0	-	0
L(2)	-	0	+	0	-
h(1)	+	+	0	-	0
h(2)	+	0	+	0	-
B(1)	-	-	0	+	0
B(2)	-	0	-	0	+
E(1)	+	+	0	-	0
E(2)	+	0	+	0	-

Table 4.1 Sensitivity table for biologically independent case

4.6.2 The Competitive Case

Recall from section 3.2 that two interacting species are said to exhibit a competitive type of biological interaction when an increase (a decrease) in the stock of one species decreases (increases) the stock of the other species. This suggests that large (small) stock of one species today implies lower (higher) stock of the other species in the future.

An increase in the discount rate should induce similar responses as in the independent case. The expected decreases in the shadow prices of both species lead to the increases in fishing efforts directed at both species, thus increasing the harvests of both species. It should be noted, however, that this can only be true if the cross-stock effects are not too large. Otherwise, the competitive nature of the species interaction dominates, whereby reducing the stock of one species increases the stock of the other species.

Following the independent case, an increase in the unit price of species 1 increases its shadow price and induces the fishermen to increase harvesting of species 1. The stock of species 1 declines, and depending on how the fishing effort on species 2 is affected, the stock of species 2 increases, thereby increasing its shadow price. In an extreme case, this might even lead to a much faster depletion of species 1. To overcome this undesirable situation, an increase in the unit price of species 1 should therefore also

induce an increase in the fishing efforts directed at species 2 (thus increasing the harvest as well) to such an extend that the 'valuable' species 1 dominates the ecosystem.

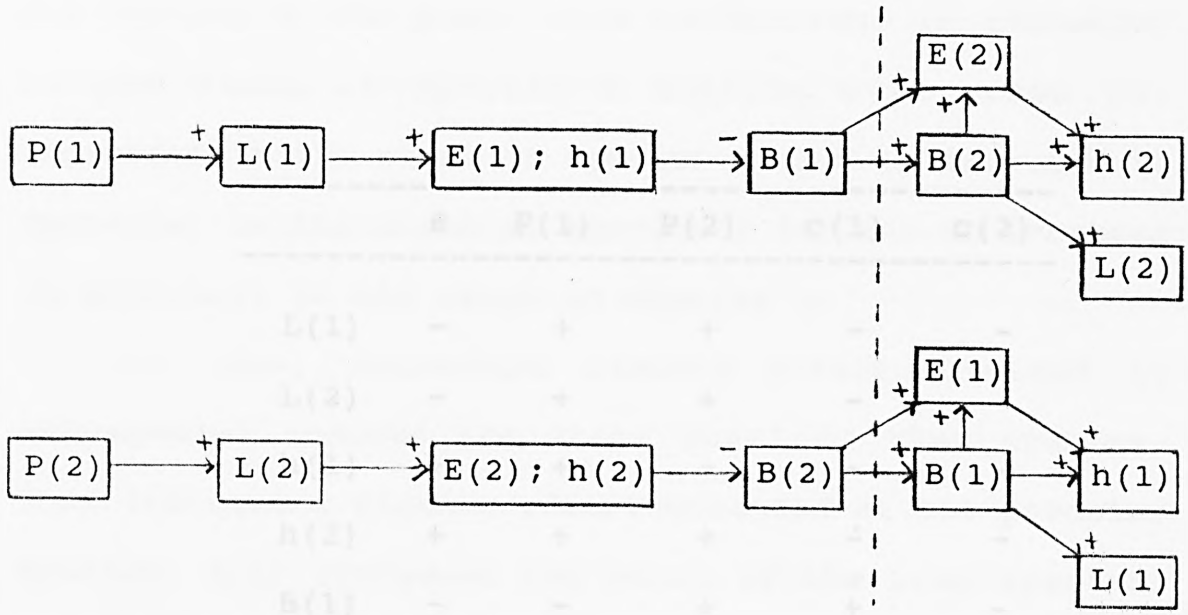
An increase in the unit price of species 2 will no doubt has a similar pattern of effect, as depicted in figure 4.3(a) — a negative effect (decrease) in its own stock and positive effects on the other endogeneous variables.

Increases in the unit cost of fishing effort or harvest should produce effects identical to that of decreases in the unit price of the species. Increasing the unit cost of harvesting of species 1 decreases its shadow price and results in a reduction in the fishing efforts directed at it. This should be followed by an increase in its own stock, and a decrease in the stock of its competitor. We would expect the fishing effort directed at species 2 to be reduced so as to avoid a much faster depletion of species 2 due to the domination of species 1 in the ecosystem. Harvest of species 2 reduces and so does its shadow price.

A similar pattern of responses — a positive effect on its own stock and a negative effect on the other endogeneous variables — should be expected following an increase in the unit cost of harvesting of species 2. This is depicted in figure 4.3(b).

The expected sensitivities for two competing species discussed above are summarised in Table 4.2.

(a) Increase in P(i)



(b) Increase in c(i)

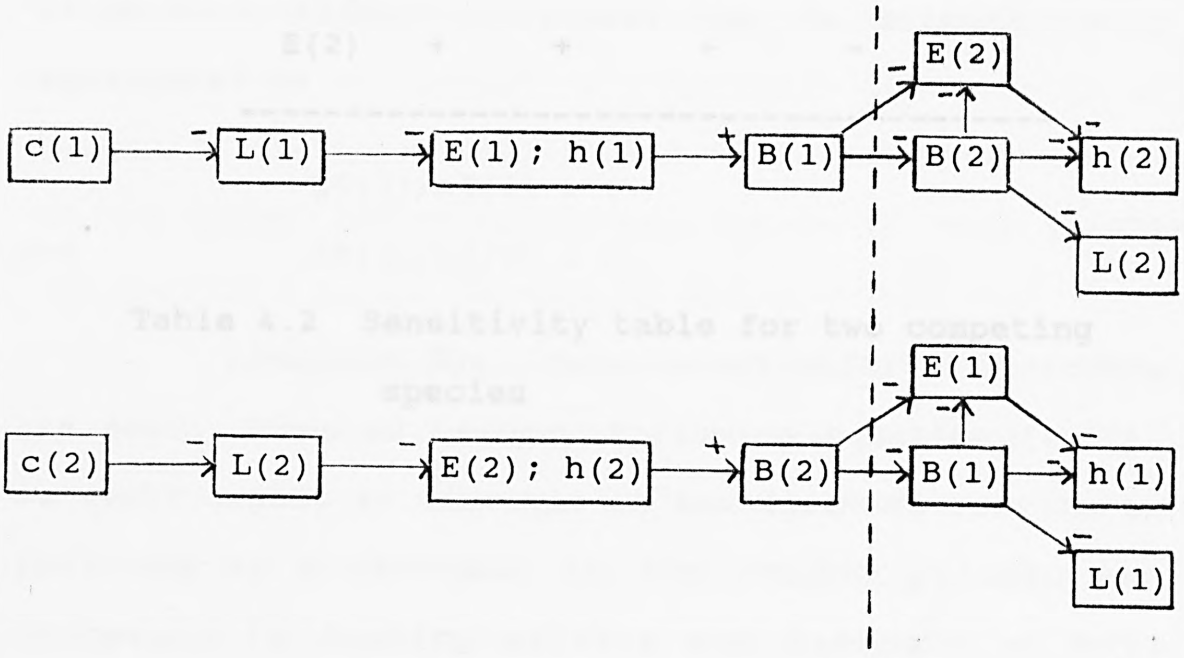


Figure 4.3 Responses in the competitive case

	θ	P(1)	P(2)	c(1)	c(2)
L(1)	-	+	+	-	-
L(2)	-	+	+	-	-
h(1)	+	+	+	-	-
h(2)	+	+	+	-	-
B(1)	-	-	+	+	-
B(2)	-	+	-	-	+
E(1)	+	+	+	-	-
E(2)	+	+	+	-	-

Table 4.2 Sensitivity table for two competing species

4.6.3 Predator-prey Case

In the predator-prey type of interaction, the effects of each stock on the growth of other is reversed. For simplicity, let species 1 be the predator and species 2 the prey. Thus an increase (a decrease) in the stock of species 1 implies a decrease (an increase) in the stock of species 2, but an increase (a decrease) in the stock of species 2 implies an increase (a decrease) in the stock of species 1.

Now, increasing fishing effort directed at any species reduces the stock level of that species. Thus increasing fishing effort directed at the predator species, E(1) increases the stock of the prey species, but increasing the fishing effort directed at the prey species, E(2) reduces the stocks of both species. These 'cross-stock-effort' responses can be mathematically represented as

$$\partial B(2)/\partial E(1) > 0$$
$$\text{and} \qquad \partial B(1)/\partial E(2) < 0. \tag{4.62}$$

Assuming the 'cross-stock-effort' responses are small, then as before, following equation (4.58), we would expect an increase in the discount rate to be followed by a decrease in the shadow prices, and increases in fishing efforts and harvests of both species. As a result, the stock of both species are reduced.

However, if the cross-stock-effort responses are large and dominant, then the total effect on the stocks following an increase in the discount rate might differ from above. If the fishing effort directed at the predator dominates, then the cross-stock-effort response associated with the prey species, $\partial B(2)/\partial E(1)$ also dominates. In this situation, the stock of the predator declines while that of the prey increases. If the effect on the prey species is strong enough, its steady state stock might increase despite increases in fishing effort directed at it. When this happens, increasing the discount rate decreases the shadow price of the predator but increases that of the prey. However, if on the other hand, the fishing effort directed at the prey species dominates then the cross-stock-effort response associated with the predator, $\partial B(1)/\partial E(2)$ is negative. In this situation, all responses should be as expected — increase in harvest of the prey, decreases in the stocks of both species and decrease in the harvest of the predator.

An increase in the unit price of the predator species induces an increase in the fishing effort directed at it, thereby increasing its harvest and reducing its stock. The stock of the prey species then increases. Also, a more valuable predator increases the value of the prey as an input to the production of the predator. Thus we would expect the shadow price of both species to increase — the predator species increases

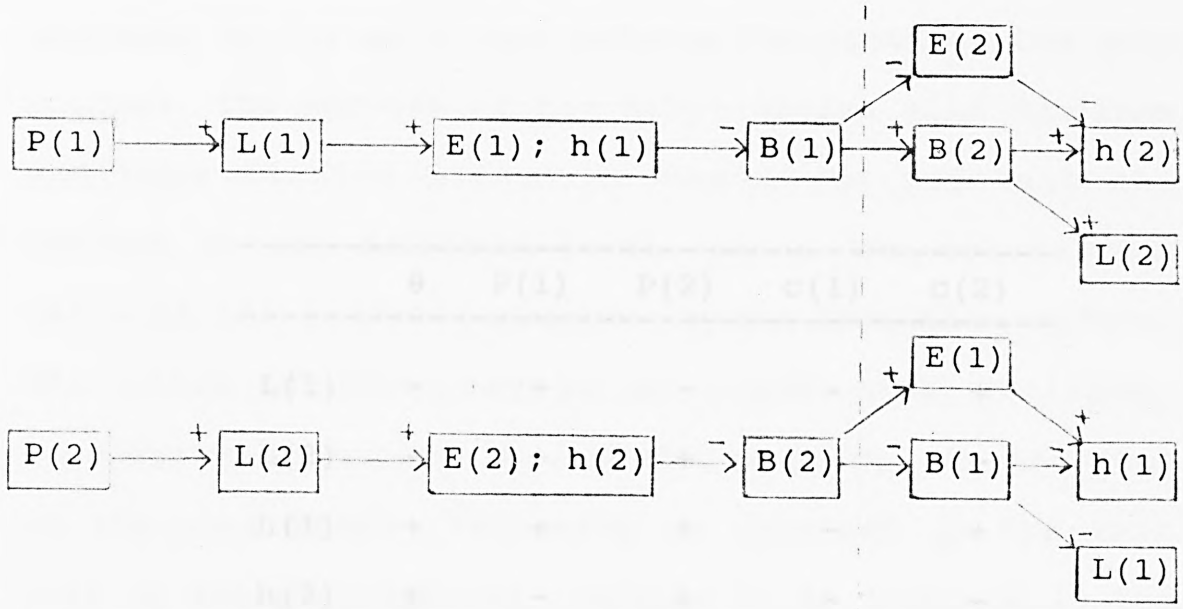
in value due to its higher price, while the prey species increases in value because of its increased value as an input. As the fishing effort directed at the predator increases, we would expect the fishing effort directed at the prey to decrease so as to leave more of the 'valuable' input unharvested.

Increases in the unit price of species 2 imply that the prey species is becoming more valuable relative to the predator. Increasing fishing effort directed at the prey reduces not only its own stock but also that of the predator. In order to protect the now valuable prey stock, we would expect the fishing effort directed at the predator to be increased so as to remove the predator from the ecosystem as quickly as possible. This also signifies a decline in the shadow price of the predator.

The above sets of responses are depicted in figure 4.4(a). Observe that we would expect the harvest of the prey species to decrease following an increase in the unit price of the predator since more prey should be left unharvested to protect the predator. In the second case, on the other hand, we would expect an increase in the harvest of the predator species following an increase in the unit price of the prey since as much predator should be harvested as possible in order to protect the prey.

An increase in the unit cost of one species decreases its shadow price. This is followed by a

(a) Increase in P(i)



(b) Increase in c(i)

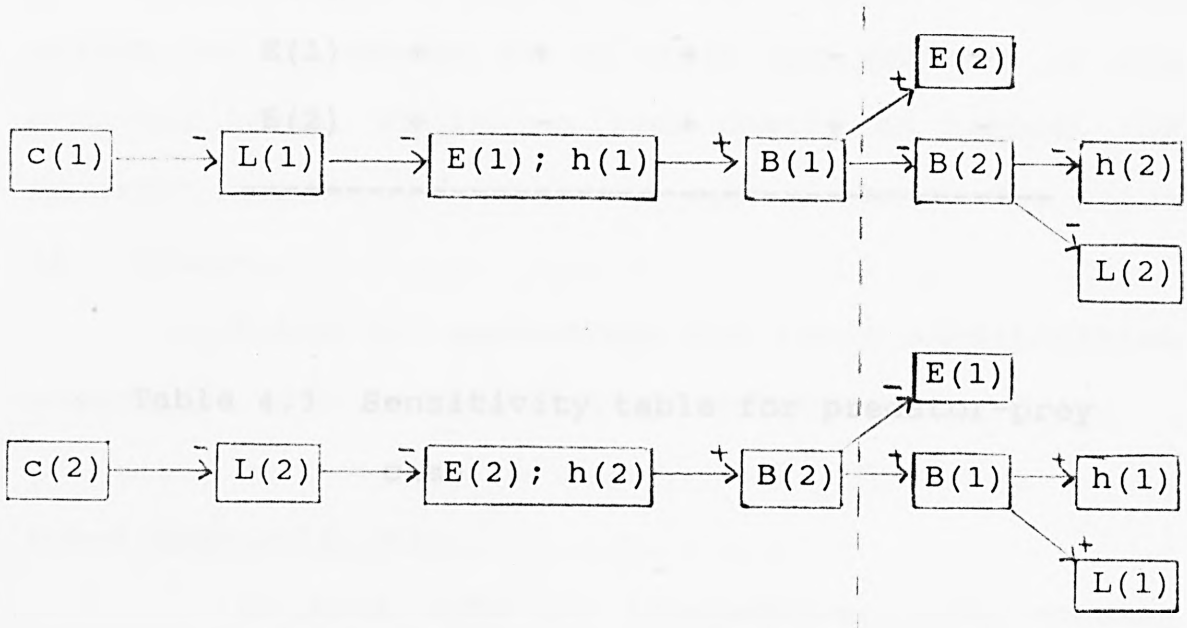


Figure 4.4 Responses in the predator-prey case

	θ	P(1)	P(2)	c(1)	c(2)
L(1)	-	+	-	-	+
L(2)	-	+	+	-	-
h(1)	+	+	+	-	+
h(2)	+	-	+	-	-
B(1)	-	-	-	+	+
B(2)	-	+	-	-	+
E(1)	+	+	+	-	-
E(2)	+	-	+	+	-

Table 4.3 Sensitivity table for predator-prey case

decrease in the fishing effort directed at it, thus reducing its harvest and increasing its stock. An increase in the predator stock as a result of an increase in its unit cost reduces the stock of the prey species. The harvest of the prey species also declines and more fishing effort is needed to maintain the harvest at any previous level. Since the net harvest value of the predator species is now less than before, the value of the prey as an input also declines, signifying a decline in its shadow price. An increase in the prey stock following an increase in the unit cost of the prey species, results in an increase in the predator stock as well. We would expect the harvest of the predator species to increase and less fishing effort is now needed to maintain the harvest at any previous level. It is now less costly to harvest the predator species and we should expect its shadow price to increase.

Table 4.3 summarises the above sensitivities associated with a predator-prey system.

4.6.4 Symbiotic Case

In this type of interaction, each species induces a positive effect on the growth of the other. Thus a larger stock of one species today implies larger stock of the other species in the future.

As in all the other cases, an increase in the discount rate reduces the shadow prices of both

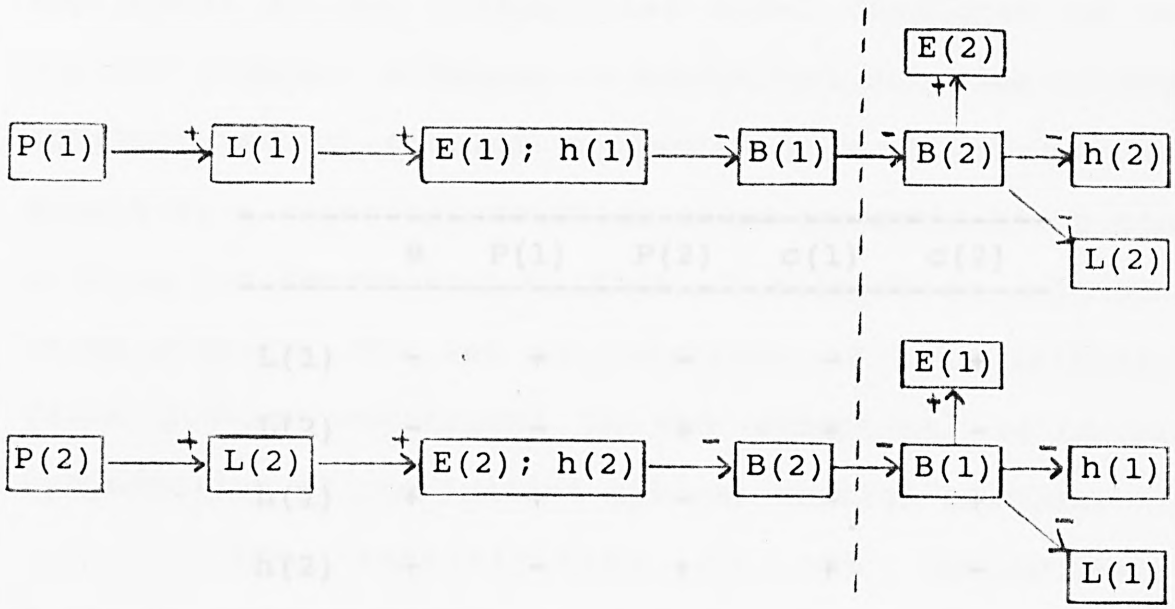
species, increases their fishing efforts and harvests and reduces their respective stock levels.

Consider a decrease in the stock level of, say, species 1 (as a result of an increase in its unit price). We would expect the stock of species 2 to decline. Harvest of species 2 also declines and more fishing effort is now needed to maintain the harvest at any previous level. The shadow price of species 2 also declines due to its reduced stock level. A similar pattern of responses should be expected of species 1 following a decrease in the stock level of specis 2.

An increase in the unit cost of harvesting of species 1 reduces its shadow price and harvest, thus leaving a higher stock level of species 1. This is followed by increases in the stock of species 2 as well as its harvest. Less fishing effort is now required to maintain the harvest of species 2 at any previous level. We should then expect the shadow price of the now-less-costly-to harvest species 2 to increase. A similar argument should be valid for species 1 following an increase in the unit cost of harvesting of species 2, as depicted in figure 4.5(b).

A summary of the responses expected in the symbiotic case is given in table 4.4.

(a) Increases in P(i)



(b) Increases in c(i)

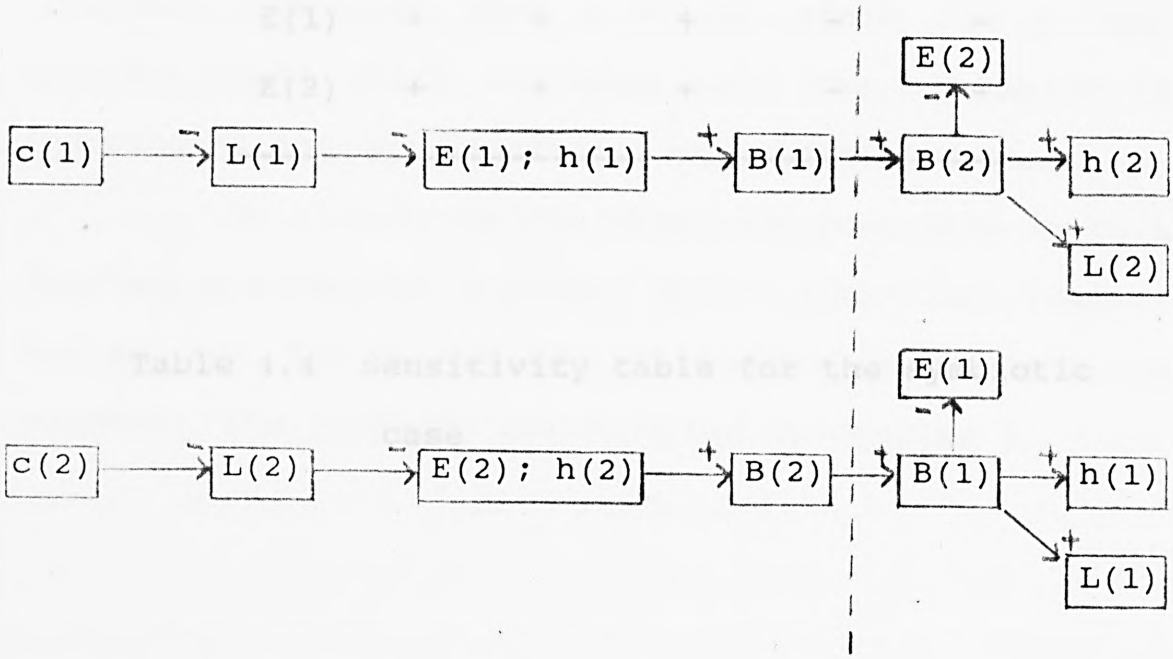


Figure 4.5 Responses in the symbiotic case

	θ	P(1)	P(2)	c(1)	c(2)
L(1)	-	+	-	-	+
L(2)	-	-	+	+	-
h(1)	+	+	-	-	+
h(2)	+	-	+	+	-
B(1)	-	-	-	+	+
B(2)	-	-	-	+	+
E(1)	+	+	+	-	-
E(2)	+	+	+	-	-

Table 4.4 Sensitivity table for the symbiotic case

4.7 Summary

In this chapter we have formulated a dynamic optimization technique in a multi-dimensional framework applicable to the multispecies model developed in an earlier chapter. Although an analytical solution to the optimal control problem presented here might not be possible, a numerical solution seems probable since the problem can be reduced to that of solving an initial-value problem. The set of solutions of this initial-value problem correspond to the suboptimal paths or trajectories of the initial optimal control problem.

The sensitivities of the endogeneous variables with respect to changes in the exogeneous variables are briefly analysed. The analysis only considers responses from a steady state for a two-species model which includes both the biologically independent and interdependent or interactive cases.

To illustrate the technique presented in this chapter, a numerical solution of the suboptimal trajectories for the North Sea multispecies fishery is computed. The findings are reported in Chapter 6.

CHAPTER 5

ESTIMATION OF BIOECONOMIC PARAMETERS

5.1 Description of the Data

In this chapter we illustrate the procedure of estimating the bioeconomic parameters that are inherent to the dynamic multispecies model developed in the study. The data are based on the time series catch-effort data of the North Sea commercial fishery published in the 'Bulletin Statistique' by the International Council for the Exploration of the Sea (ICES) covering the time period 1960-1975. This limited choice of time period is largely due to the unavailability of the fishing effort data after that period. The total harvests of each species were recorded in terms of an aggregate biomass in metric tons, treating them as though they were uniform. Although they were grouped according to species, no distinction were made between individuals according to their sex, age or size. Hence the population stock level to be estimated will also be expressed in terms of the aggregate biomass in metric tons.

In fishery studies, the total harvest is the most vital information without which any assessment studies are meaningless. Thus the data on harvest should include all removals from the stock by all the fisheries. However, it is most often that the least valuable species (due to its small size or of undesi-

rable species) are discarded at sea and not recorded. The statistics on total harvests are therefore mostly of 'nominal harvest'. In absence of some estimates of the discards, any assessment of the full impact of fishing on the stocks is bound to be less accurate, and conclusions reached might depart from reality to some extent.

Fishing activity in the North Sea during the time period covered was mainly based on an open-access common property fishery involving many fishing nations — Belgium, Denmark, France, German Democratic Republic (GDR), Federal Republic of Germany (GFR), Netherlands, Norway, Poland, Sweden, United Kingdom (England, Wales and Scotland) and Russia (USSR). However, no data was reported by Denmark, France and Sweden during that period. Their harvests were only recorded in the bulletin from 1976, 1978 and 1979 onwards respectively. During the period 1963-1972, the recorded Norwegian catch-effort data were based solely on a single type of fishing vessel, the bottom otter trawls. No Norwegian or Russian data was available before 1963.

Data on fishing effort are normally used for two distinct purposes. Firstly, in stock assessment as a measure of fishing mortality, and secondly in general economic studies as a measure of the cost of fishing. The types of informations collected normally include the number of fishing vessels in operation, their main characteristics (such as tonnage, horsepower), the type

of fishing gear and other equipment, and the time spent fishing and the number of operations.

All the catches in the stock as well as all fishing on the same stock should be accounted for in calculating the amount of fishing. This calls for data on fishing efforts from all components of a fishery — a requirement seldom met in practice, and total effort is usually estimated from data on a part of the fishery only. With reference to the North Sea commercial fishery, the data for the time period covered by the study were incomplete. Some informations on fishing effort were missing for some of the years as well as for some of the nations and some fishing vessels. Although some informations on capital (in term of the number of vessels in operation) and labour (in term of the number of fishermen employed) were available for some nations in some years, they were insufficient to be incorporated into the fishing effort.

With the adoption of the 200-mile Exclusive Economic Zones (EEZs) by the coastal countries in 1977, the management of the North Sea then came under the jurisdiction of the European Economic Community (EEC). This resulted in the evictions of most of the non-EEC fishing fleets from the North Sea (particularly those from the Eastern-bloc).

5.2 Estimation of Fishing Effort

Inspection of equation (3.49) tells us that to compute the composite fishing effort we must first choose a suitable type of fishing vessel and/or gear to act as a 'standard' fishing vessel and/or gear. After comparing the data corresponding to the various fishing vessels and gears during the time period 1960-1975, 'the bottom otter trawl' was chosen to act as a standard fishing vessel, and all fishing efforts will therefore be expressed in its equivalent form. This choice is largely due to the availability of the annual catch-effort data corresponding to the bottom otter trawls for every year during the period taken for the study. Furthermore, eight nations — Belgium, GDR (from 1973), GFR, Norway (from 1963), Netherlands (from 1961), Poland, United Kingdom and Russia (from 1963) — had their catch-effort data corresponding to the bottom otter trawls recorded (ICES, 1960-1975). Thus the choice of the bottom otter trawl as a standard fishing vessel seemed most appropiate since not only it represented the majority of the fishing nations operating in the North Sea but also had an almost complete recorded annual catch-effort data for the time period covered.

Although one might consider using a smaller (or national) index, for example UK otter trawl of size L, say as a standard fishing vessel since the estimated parameters based on it are likely to be less biased

than those estimated using an international index, the inconsistency of the annual catches recorded by these national vessels makes it a less suitable candidate for standard fishing vessel. UK fishing vessels, for example, were actively fishing in the North Sea only after the adoption of the 200-mile EEZ. Prior to that most of the UK fishing vessels were engaged in distant water fisheries. Furthermore, as an example, the North Sea mackerel fishery was subjected to strict regulations by UK government during some of the period and as a result only a very small percentage of catches were recorded by UK vessels whereas mackerel became one of the most fished species (in term of the international harvests) in the North Sea after the decline of the herring fishery. Thus a total international specific fishing vessel (for example total bottom otter trawl from all nations) operating on the fishing ground is more likely to exhibit consistent annual catches, and thus suits better as a standard fishing vessel.

The fishing vessels in operation were also categorised in terms of sizes, namely the average gross registered tonnage (GRT) and the engine capacity, the horsepower (HP). With reference to the bottom otter trawls, a complete record of the average GRT was available for five nations — GDR, GFR, Norway, Netherlands and UK. The average GRT for Belgium and Russian bottom otter trawls were only recorded from 1972 onwards, whereas those of the Polish fishing vessels

were recorded only for the period 1960-1967.

However, the average GRTs for these bottom otter trawls for the years in which they were not recorded can be estimated. Assuming the GRT for a given size class of fishing vessel does not fluctuate significantly from year to year (this is justified by inspecting the number of fishing vessels entering and leaving the tonnage class from year to year as given in the bulletin (ICES, various years)), we can use the average GRT recorded in previous year or next nearest year as an approximate average GRT for that year.

The fishing efforts reported were expressed in various forms such as the number of hours spent fishing, the number of days spent fishing, the number of days at sea and the number of trips made, depending on the fishing nation referred to. For example, Belgium, Norway, Netherlands, Poland, UK and USSR expressed their fishing times in terms of the number of hours fishing. This is the number of hours during which the vessels were in the water and fishing (ICES, various years). GFR, on the other hand, expressed all its fishing times in terms of the number of days spent fishing for the period 1960-1971, and in terms of both the number of hours fishing and the number of days fishing for the period 1972-1975.

For consistency, we need to express all the fishing times in a single unit, the hours fishing, before we can compute the composite fishing efforts.

Thus for the German bottom otter trawls we need to estimate the number of hours fishing during the period 1960-1971 from the recorded number of days fishing.

Now, assuming that hours fishing, for a given fishing vessel in a given tonnage class, is related to days fishing only, we can write

$$HF = f(DF), \tag{5.1}$$

where DF is the days fishing and HF is the hours fishing. Equation (5.1) states that once on the fishing ground, all fishing vessels of the same category and tonnage class will on average spend an approximately equal number of hours fishing for a given number of days fishing.

Three types of functions — linear, loglinear and exponential — were estimated for various tonnage class by Ordinary Least Square (OLSQ) method using the data from the period 1972-1975. The results are summarised in Appendix A.

All regression results suggested that linear and loglinear functions were better estimates than the exponential function. However, a loglinear relation of the form

$$\log (HF) = A \log(DF) + \log B, \tag{5.2}$$

which is equivalent to

$$HF = B.(DF)^{A} \tag{5.3}$$

gave large numerical values for the parameter B as follows :

$$HF = \begin{cases} 1038(DF)^{0.9918} & \text{for GRT (0-150)}, \\ 230(DF)^{1.0477} & \text{for GRT (151-300)}, \\ 275(DF)^{1.0616} & \text{for GRT (600-1000)}. \end{cases} \quad (5.3)$$

Since $A \simeq 1$, this implies a very large number of hours fishing for a relatively small number of days fishing. In most cases, it is more than 24 hours fishing for each day fishing !

Thus, without loss of generality, we can assume a linear relation of the form

$$HF = A(DF) - B \quad (5.5)$$

where A, B are positive constants, and valid for $DF > B/A$ since $HF > 0$. Substituting the numerical values for A and B, equation (5.5) becomes

$$HF = \begin{cases} 19.389(DF) - 6.91, & \text{for GRT (0-150)} \\ 15.285(DF) - 111.22, & \text{for GRT (151-300)} \quad (DF > 8) \\ 13.965(DF) - 0.01, & \text{for GRT (600-1000)}. \end{cases} \quad (5.6)$$

It should be noted that no German bottom otter trawl of tonnage class (301-599) was reported to be in operation in the North Sea during 1960-1975.

Also, as can be seen, relation (5.6) implies that the intercept is not at the origin. This suggests that some hours fishing is usually lost for each day fishing. However, since the total number of days fishing is usually large, the average hours fishing lost is relatively small.

Equation (5.6) was then used to estimate the number of hours fishing by the German bottom otter trawls for each class of average GRT for the period 1960-1971.

Two measures of fishing effort were then estimated for the bottom otter trawls — the total number of hours fishing (HF) and the total ton-hours fishing (TH). The latter is the product of the number of hours fishing and the average GRT of the fishing vessels. These two measures of fishing effort for the 'standard ' fishing vessel (the bottom otter trawl) and the species caught are tabulated in table 5.1.

5.3 Estimation of Biological Parameters and Q(i)

A total of nine main species comprising of six demersal and three pelagic were chosen to illustrate the multispecies model developed in the study. These species were numbered as follows:

1. European Plaice,
2. Common Sloe,
3. Atlantic Cod,
4. Haddock,
5. Saithe,
6. Whiting,
7. Atlantic Herring,
8. Sprat,
9. Atlantic Mackerel,
10. Others.

All other species such as hake, Norway pout, picked dogfish, etc were classified under 'others'.

Year	Fishing Effort		Harvest in metric tons			
	'000HF	'000TH	Plaice	C.Sole	Cod	Haddock
1960	2786	366716	39880	14757	42758	31259
1961	3066	832582	37842	18497	37395	29080
1962	2667	346269	42794	19857	35760	25021
1963	2466	417409	50799	21884	35886	21885
1964	2442	414827	51828	6507	39873	38817
1965	2177	404649	44777	9137	59270	43793
1966	2485	604258	45350	11098	92376	129724
1967	2212	489078	42610	6763	114252	75408
1968	2177	783722	38604	5364	119440	42757
1969	2018	333640	37986	3296	78491	246624
1970	1977	331688	41355	3713	98438	409420
1971	2103	303863	35857	3337	128659	136104
1972	2184	281589	35178	3315	98219	78912
1973	2660	432276	33706	7000	85807	100322
1974	1289	131703	1910	2130	11848	43469
1975	1686	246115	4531	2720	32933	50197

Year	Harvest in metric tons						
	Saithe	W'ting	Herring	Sprat	M'rel	Others	TOTAL
1960	9398	17504	118238	1947	36113	31918	343772
1961	7637	18154	118877	1721	38520	33389	341112
1962	7855	26081	95792	4544	30574	29605	317883
1963	8519	17642	119610	9339	6708	43105	335377
1964	8845	14917	146779	19777	13911	43794	385048
1965	12933	19103	115199	6499	5172	36558	352441
1966	41287	44848	100946	4836	6201	37277	513943
1967	24712	20131	46069	13065	7284	34881	385175
1968	25824	29437	21188	14481	5706	31384	334168
1969	45510	20524	45565	3900	856	33296	516048
1970	81467	29424	32677	5655	1331	32468	736304
1971	122740	16962	6511	5274	3149	42349	500982
1972	21478	18844	14380	16202	1934	130771	419233
1973	122357	22467	29429	35508	15653	239537	691786
1974	110781	9512	8155	31807	3996	332898	513037
1975	158263	14370	14838	50280	9468	369218	706818

Source: ICES, Bulletin Statistique, (1960 - 1975)

Table 5.1 Fishing efforts and harvests in the North Sea for bottom otter trawls, 1960-1975

The total recorded harvests from the North Sea by species (ICES, 1960-1975) and the catch-effort data of table 5.1 were then used to compute the equivalent composite fishing efforts directed at each species, E(i,t), i=1,..,10, for the two measures of fishing efforts. Parameters relating to the model given by equation (3.32) were then estimated by Ordinary Least Square Method (OLSQ) using the Time Series Processor package (TSP — version 4.0J) for both measures of fishing efforts.

The model, which is a linear equations model consists of ten equations for each measure of fishing effort. The model is also a simultaneous equations model since its variables simultaneously satisfy all the equations. Annual time series data were used in the regression to cover a period of sixteen years, 1960-1975. There were data available prior to this period, but it is inconsistent within different sources as well as less complete. These regression results are summarised in Appendices B and C where each equation is presented with its estimated coefficients and the following statistical tests:

1. The coefficient of multiple determination, R^2 which measures the proportion of the variation in the dependent variable 'explained' by the variation in independent variables;
2. The F-statistic, which tests the significance of the relationship between the dependent variable and all

of the explanatory variables in the equation; in other words, to test the significance of R^2;

3. The Durbin-Watson statistic, D-W which tests for the presence of autocorrelated disturbances in the equation; and finally
4. The t-statistic which determines the significance of the estimated coefficient, and is given in parentheses under the estimated coefficients.

5.3.1 Species Combinations

Initially, it was assumed that all species do exhibit significant form of biological interactions with each other. But the low values of the F-statistics obtained for most of the combinations suggested otherwise — some of the coefficients were therefore significantly zero. Various species combinations were then tested for each regression, deleting and introducing each species into the regression equations until a set of 'satisfactory' combinations was obtained. Three main conditions were imposed in deciding which combinations were the best satisfactory combinations. These were:

1. positive relative growth rate for all species, that is, $r(i) > 0$, for all $i=1,...,10$;
2. positive catchability coefficient for all species, that is, $Q(i) > 0$, for all $i=1,...,10$; and
3. negative self-interacting coefficient for all species, that is $A(i,i) < 0$, for all $i=1,..,10$;

(or equivalently, $a(i,i) < 0$, for all $i=1,\ldots,10$).

The 'probable' sets of species combinations suggested by the final regression results were found to differ for the two measures of fishing efforts.

Case I: Fishing Effort in '000HF

In the regressions, time averages $T = 1,\ldots,5$ years were used. The results for the 'best' time average are summarised in Appendix B and were found to differ from species to species. The values of the coefficient of multiple determination or correlation, R^2 were generally quite high, ranging from 0.557 for species 8 to 0.999 for species 7 and 9. Except for species 7 and 9, not all of the parameters estimated were statistically significant (generally low t-statistic values) despite their relatively high R^2 values.

The F-statistics vary from a low 1.46 for species 4 to a high 908.20 for species 7, implying a very wide range of significant level from less than 0.1 percent (for species 7 and 9) to more than 10 percent.

Based on the D-W statistics, three of the regression results, associated with species 1, 4 and 10 appear to indicate the possible absence of autocorrelation. Their values are much closer to 2. Result associated with species 8 seems to suggest a possible preesence of positive autocorrelation while the remaining results point to the possible presence of negative autocorrelation. However, the program, TSP used to

estimate these equations has no capability of treating the autocorrelation problems.

The estimated values of the relative rate of growth, r(i) and the relative catchability coefficient, Q(i) for each species i=1,...,10 are tabulated in table 5.2. The relative rate of growth varied from a low 0.2678 for species 1 to a relatively very high 34.896 for species 6. Except for species 8 and 9, the relative catchability coefficients were of order 10^{-5}.

The coefficient of species interaction, a(i,j), i,j=1,...,10 computed from the estimated parameters are given in table 5.3. Their order of magnitudes ranged from 10^{-8} to 10^{-5} with $a(i,i) < 0$ for all i=1,...,10 as required, and a(i,j) assuming positive, negative and zero values for $i \neq j$. The signs of these coefficients implied the existence of all three types of species interactions discussed in Chapter 3. This is illustrated in table 5.3, with the predator-prey interactions diagramatically represented in figure 5.1 where the arrows point to the predators (for example, the predation of species 6 and 7 by species 1). The main predator group appeared to comprise of species 1, 4 and 8, while species 5 and 6 constituted the main prey group. All other species were 'intermediate' species, being both preys as well as predators, for example species 3 was a prey to species 9 but a predator to species 6. Observe that species 2, 9 and 10 formed a 'cyclic' predator-prey interaction.

Species i	F.Effort in '000HF		F.Effort in '000TH	
	r(i)	Q(i)	r(i)	Q(i)
1. Plaice	0.2678	1.6410×10^{-5}	1.2671	2.0733×10^{-7}
2. C.Sole	1.8032	2.8800×10^{-5}	2.3080	5.0716×10^{-8}
3. Cod	1.0547	4.2750×10^{-5}	1.2922	2.3633×10^{-7}
4. Haddock	1.9589	3.5828×10^{-5}	1.0384	7.3993×10^{-7}
5. Saithe	3.4874	1.5981×10^{-5}	5.0996	5.0462×10^{-7}
6. Whiting	34.896	4.3707×10^{-5}	2.7441	1.7590×10^{-7}
7. Herring	11.832	1.0385×10^{-5}	4.9070	7.5634×10^{-8}
8. Sprat	0.6352	5.8490×10^{-6}	0.9502	1.1476×10^{-7}
9. Mackerel	2.4874	8.8135×10^{-7}	1.0510	1.3014×10^{-8}
10. Others	2.1669	2.4874×10^{-5}	2.9978	7.2903×10^{-8}

Table 5.2 The estimated r(i) and Q(i)

j	a(1,j)	a(2,j)	a(3,j)	a(4,j)	a(5,j)	a(6,j)	a(7,j)	a(8,j)	a(9,j)	a(10,j)
1:	-6.5185E-8 (-,-)	...	...	...	...	-9.6008E-6 (-,+)	-4.5126E-6 (-,+)	...	...	...
2:	...	-6.8167E-7 (-,-)	...	3.3062E-6 (+,-)	-2.7849E-6 (-,+)	-1.7659E-5 (-,-)	5.6480E-6 (+,+)	1.4623E-6 (+,+)	-1.1903E-6 (-,+)	7.2377E-7 (+,-)
3:	...	...	-1.1693E-7 (-,-)	...	...	-7.9241E-6 (-,+)	...	...	9.1626E-8 (+,-)	...
4:	...	-2.6501E-7 (-,+)	...	-6.7188E-7 (-,-)	...	-1.0939E-7 (-,+)	-7.3999E-7 (-,-)	...	1.9697E-7 (+,+)	-1.5324E-7 (-,-)
5:	...	2.6047E-7 (+,-)	...	...	-7.7596E-7 (-,-)	-5.3853E-7 (-,-)	8.1930E-7 (+,-)	...	-4.5717E-7 (-,-)	3.6402E-7 (+,+)
6:	1.8933E-6 (+,-)	-3.9359E-6 (-,-)	2.3561E-6 (+,-)	3.3929E-6 (+,-)	-5.4673E-6 (-,-)	-1.2201E-5 (-,-)	-1.5164E-5 (-,-)	4.4131E-7 (+,-)	-3.7060E-6 (-,-)	-2.4571E-6 (-,-)
7:	1.0448E-7 (+,-)	2.0737E-8 (+,+)	...	-4.3751E-7 (-,-)	-1.4124E-7 (-,+)	-6.1868E-7 (-,-)	-3.4177E-7 (-,-)	...	-3.0581E-8 (-,-)	-1.6383E-7 (-,-)

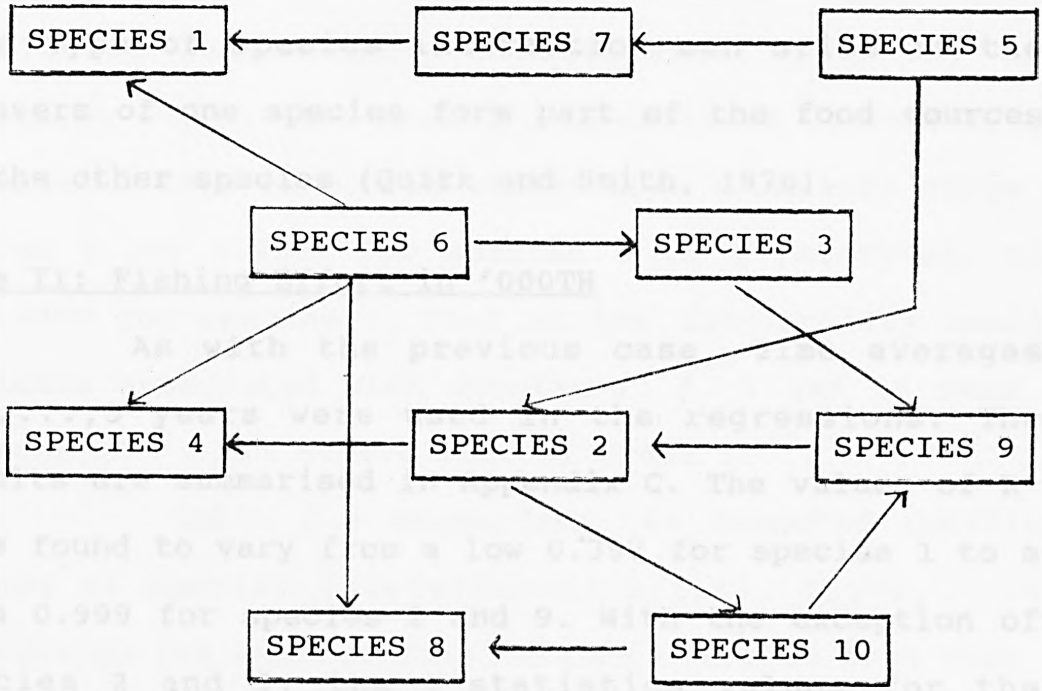
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j	a(1,j)	a(2,j)	a(3,j)	a(4,j)	a(5,j)	a(6,j)	a(7,j)	a(8,j)	a(9,j)	a(10,j)
8:	...	2.1496E-8 (+,+)	...	...	...	-2.6121E-7 (-,+)	2.2658E-7 (+,0)	-1.5727E-7 (-,-)	-1.8163E-6 (-,-)	-4.5941E-8 (-,+)
9:	...	3.1921E-8 (+,-)	-6.4703E-8 (-,+)	4.1661E-9 (+,+)	-9.6693E-8 (-,-)	-7.7761E-7 (-,-)	-3.6160E-7 (-,-)	-1.5175E-8 (-,-)	-1.5257E-7 (-,-)	-2.8161E-8 (-,+)
10:	...	-2.7110E-8 (-,+)	...	-6.0904E-8 (-,-)	1.5401E-7 (+,+)	-1.1179E-6 (-,-)	-1.2124E-6 (-,-)	7.4508E-7 (+,-)	9.6765E-7 (+,-)	-2.8212E-7 (-,-)

Note: The letter E refers to the power of ten such that aE-n implies $a.(10^{-n})$.

The signs in the brackets refer to the types of species interactions : (-,-) for competition,
(+,-) for predator-prey, and
(+,+) for symbiotic case.
(see text for (+,0)).

Table 5.3 Coefficients of species interactions, a(i,j)
(fishing effort in '000 hours fishing)



Note: The arrows point to the predators.

Figure 5.1 Predator-prey interaction
(fishing effort in '000HF)

The results also suggested a probable fourth species interaction between species 7 and species 8. Here $a(7,8) > 0$ while $a(8,7) = 0$. Thus species 8 appeared to exhibit an accelerating effect on the growth rate of species 7 while species 7 appeared not to exhibit any effect on the growth rate of species 8. This type of species interaction can arise if the cadavers of one species form part of the food sources of the other species (Quirk and Smith, 1970).

Case II: Fishing Effort in '000TH

As with the previous case, time averages $T=1,\ldots,5$ years were used in the regressions. The results are summarised in Appendix C. The values of R^2 were found to vary from a low 0.397 for species 1 to a high 0.999 for species 2 and 9. With the exception of species 2 and 9, the t-statistics values for the estimated parameters were generally low.

Two of the regression results associated with species 2 and 9 produced a very high F-statistic value equivalent to significant levels of less than 0.1 percent each. Other results produced F-statistic values whose equivalent significant levels vary from 0.5 percent to more than 10 percent. The D-W statistics produced by the regressions appear to suggest the possible absence of autocorrelation for equations associated with species 3 and 6, the possible presence of positive autocorrelation for equations associated

with species 1 and 4, and negative autocorrelation for the remaining equations. As mentioned earlier, the TSP program has no capability to treat these autocorrelation problems.

Table 5.2 also gives the estimated values for the positive relative rate of growth, r(i) and the relative catchability coefficients, Q(i) for each species i=1,...,10. However, in contrast to case I, the relative rate of growth varied over a smaller range — from a low 0.9502 for species 8 to a relatively high 5.0996 for species 5. Four of the catchability coefficients associated with species 2, 7, 9 and 10 were of order 10^{-8}. All others were of order 10^{-7}.

Table 5.4 summarises the computed coefficients of species interactions, a(i,j), i,j=1,...,10. Although the species combinations differed from case I, the order of magnitudes of these coefficients also ranged from 10^{-8} to 10^{-5} with a(i,i) < 0 for all species. As before, a(i,j), i,j=1,...,10, $i \neq j$, were found to assume positive, negative and zero values, thus implying the existence of all the three types of species interactions (table 5.4).

A diagramatical representation of the predator-prey interaction is given in figure 5.2 with the arrows pointing to the predators. In this case, species 6 and 7 appeared to constitute the main predator group while species 1, 3 and 5 made up the main prey group. All other species (except species 8)

j	a(1,j)	a(2,j)	a(3,j)	a(4,j)	a(5,j)	a(6,j)	a(7,j)	a(8,j)	a(9,j)	a(10,j)
1:	-2.3275E-7 (-,-)	3.1423E-6 (+,+)	...	...	7.5367E-6 (+,+)	...	3.8758E-5 (+,-)	...	2.3831E-5 (+,-)	...
2:	1.1381E-6 (+,+)	-9.7628E-8 (-,-)	...	3.9691E-7 (+,-)	1.1563E-6 (+,+)	6.9882E-7 (+,-)	-6.5976E-6 (-,-)	1.5107E-6 (+,+)	-5.3191E-6 (-,+)	3.5986E-6 (+,+)
3:	...	...	-7.1674E-7 (-,-)	...	...	...	-8.3001E-6 (-,-)	...	-5.9879E-6 (-,-)	6.3296E-7 (+,-)
4:	...	-5.5861E-7 (-,+)	...	-8.5928E-7 (-,-)	...	5.0172E-7 (+,-)	-6.3065E-6 (-,-)	...	-1.1120E-6 (-,+)	...
5:	2.6702E-7 (+,+)	1.9957E-6 (+,+)	...	...	-2.6641E-6 (-,-)	9.8007E-7 (+,-)	6.4899E-7 (+,-)	...	-3.9869E-6 (-,-)	3.5521E-6 (+,+)
6:	...	-1.0815E-5 (-,+)	...	-6.2457E-7 (-,+)	-1.8246E-5 (-,+)	-8.2370E-7 (-,-)	-7.5969E-6 (-,-)	...	-5.7211E-7 (-,-)	-1.0652E-5 (-,-)
7:	-6.6258E-8 (-,+)	-3.2427E-7 (-,-)	-6.1605E-8 (-,-)	-1.9451E-7 (-,-)	-8.2055E-8 (-,+)	-7.7933E-8 (-,-)	-3.3534E-6 (-,-)	-2.6603E-7 (-,-)	-1.9960E-6 (-,-)	-6.1502E-7 (-,+)

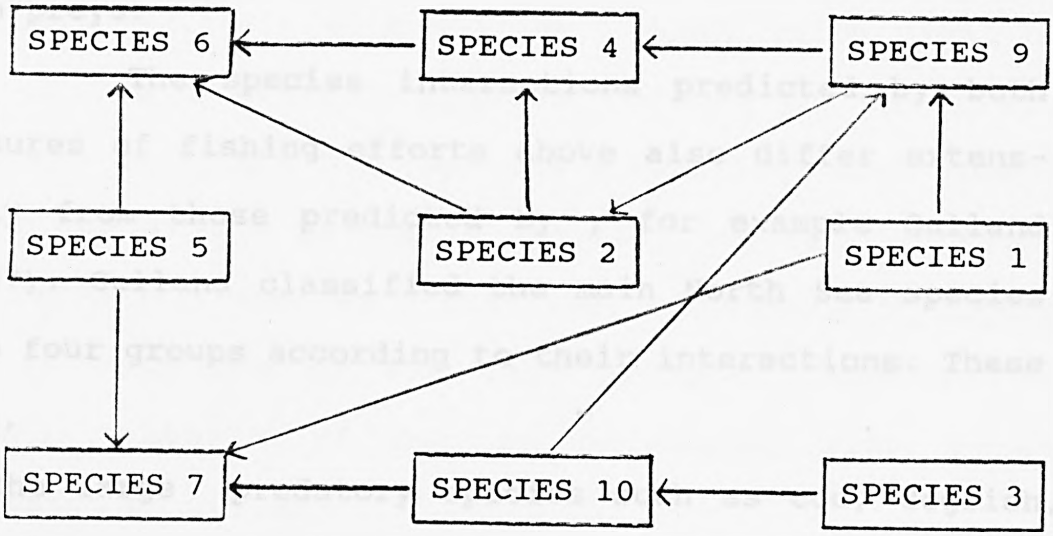
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j	a(1,j)	a(2,j)	a(3,j)	a(4,j)	a(5,j)	a(6,j)	a(7,j)	a(8,j)	a(9,j)	a(10,j)
8:	...	5.8491E-7 (+,+)	...	...	...	...	-1.7243E-5 (-,-)	-2.0314E-7 (-,-)	-1.3660E-5 (-,-)	3.6986E-6 (+,+)
9:	-9.4380E-8 (-,+)	1.3289E-8 (+,-)	-8.6386E-8 (-,-)	2.4798E-8 (+,-)	-2.7499E-7 (-,-)	-1.2454E-7 (-,-)	-6.4506E-8 (-,-)	-5.1019E-8 (-,-)	-1.9240E-7 (-,-)	-2.2072E-7 (-,+)
10:	...	1.0491E-7 (+,+)	-2.2971E-8 (-,+)	...	1.5414E-7 (+,+)	-1.9031E-8 (-,-)	1.1323E-6 (+,-)	1.5473E-7 (+,+)	1.0691E-6 (+,-)	-3.7481E-7 (-,-)

Note: The letter E refers to the power of ten such that aE-n implies $a.(10^{-n})$.

The signs in the brackets refer to the types of species interactions : (-,-) for competition
(+,-) for predator-prey, and
(+,+) for symbiotic case.

Table 5.4 Coefficients of species interactions, a(i,j)
(fishing effort in '000 ton-hours fishing)



Note: The arrows point to the predators

Figure 5.2 Predator-prey interaction
(fishing effort in '000TH)

were intermediate species.

As can be seen, the species combinations and interactions predicted differed for the two cases. For example, results using hours fishing as unit of fishing effort suggested species 1 as one of the main predators, while results using ton-hours fishing as unit of fishing effort suggested it to be one of the main preys.

The species interactions predicted by both measures of fishing efforts above also differ extensively from those predicted by , for example Gulland (1987). Gulland classified the main North Sea species into four groups according to their interactions. These were,

1. the large predatory species such as cod, dogfish, saithe and also probably whiting. These species exhibit strong effects on the survival of all the smaller species.
2. species that do not have strong effects on other groups. Included in this group are haddock, plaice and other demersal species.
3. the preys of group 1, such as herring and mackerel, the two most commercially important pelagic species. This group might also affect the recruitment to groups (1) and (2).
4. species fished wholly for industrial purposes such as sandeel, Norway pout and other species. These are also the preys of group (1), and might affect the

recruitment of other groups.

From figures 5.1 and 5.2 it can be seen that most of the predator-prey interactions predicted by the model are not in complete agreement with those suggested by Gulland. For example, the model predicted species 5 (saithe) to be one of the prey species but Gulland regarded it as one of the large predator species. Similarly with species 3 (cod) which might be one of the predatory species instead of the prey. However, in figure 5.2, species 8 (whiting) does appear to be one of the predatory species, but not according to figure 5.1. Species 7 (herring), according to figure 5.2 is also one of the main predatory species — another example of not in agreement with those suggested by Gulland.

It thus appears that the species interactions predicted by the two measures of fishing efforts depart quite extensively from those suggested by Gulland. However, species interactions can occur at all stages of life, thereby reversing the roles of predator and prey. For example (Gulland, 1987), the eggs of larvae of cod might be subjected to predation by an adult herring or mackerel. But an adult cod can be an active predator on herring.

To fully account of all the possible interactions which are enormous and complex would be difficult. More extensive and detailed informations are required.

These less than satisfactory regression results (for both measures of fishing efforts) can be attributed to various reasons. The estimated coefficients in the model might be changing over time. This is usually regarded as structural change and may occur gradually over several years, or suddenly as a shift between adjacent years.

The functional form used in the specification of the model may be only approximately correct as in the case of the biological growth function where the true form is unknown. In this case, the regression coefficients become sensitive to the subset of the data used in the estimation procedure because the functional form fails to reflect the 'actual' relationship between the dependent and independent variables.

A variable (or variables) which actually influences the dependent variables is either excluded or misspecified. For example, the equilibrium population, B_k has been assumed constant in the present model. If it is in fact changing, then variables describing how it changes should be included in the equation. Also, capital and labour are excluded from the production function. There is a strong belief that capital and labour do matter in the production of fish. Although various measures of fishing efforts — the number of time spent fishing, characteristic of fishing vessels, etc — are available, they do not substitute for the direct measurement of capital and labour.

However, to include capital and labour in the production function is not possible since data on them has not been sufficiently collected.

Finally, even assuming knowledge of the correct functional form and effects to include in the model, the poor quality of the data can and does affect the regression results significantly. In a few instances, some of the data were missing (for example the number of hours fishing by German bottom otter trawls) and in those cases, the available data were used to estimate the missing data. This is likely to produce a less satisfactory estimates but seems to be the least time consuming remedy.

Thus results associated with the estimation of parameters and species interactions are likely to be less accurate than those estimated or predicted by others. At best, they can be regarded as 'most probable' estimates. The positive conclusion might be that the models and the data are less consistent with each other.

However, this 'most probable' estimates will be adopted in the study to illustrate the applicability of the optimization technique developed in the previous chapter in determining the suboptimal time paths in this 'most probable' multispecies scenerio.

5.3.2 Estimation of Stock Levels

Once the relative catchability coefficients corresponding to each species are known, their respective stock levels can then be computed from their harvest (production) functions,

$$h(i,t) = Q(i)E(i,t)B(i,t), \quad i=1,\ldots,10. \qquad (5.7)$$

Tables 5.5 to 5.14 give the computed estimated stocks of each species in metric tons for both measures of fishing effort for the period 1960-1975. Where possible comparisons are also made by those estimated by others. A graphical representations of these estimated stocks are given in figures 5.3 to 5.11 for nine of the species. For convenience, we will refer to the fishing effort measured in hours fishing as the first fishing effort and those measured in ton-hours fishing as the second fishing effort.

For species 1 (plaice) the stocks estimated by the first fishing effort were generally much higher than those estimated by the second fishing effort, and slightly higher than those estimated from virtual population analysis (Bannister, 1978). Despite the differences in their levels, the patterns exhibited by both estimated stocks during 1960-1975 were found to be quite similar — a relatively low stocks in 1961 and 1968, a relatively high stocks in 1964 and 1970, and a very much reduced stocks to less than 100000 metric tons in 1974.

The stocks of species 2 (common sole) estimated by the second fishing effort were generally much higher than those estimated by the first fishing effort. From mid-sixties, the stocks estimated by the first fishing effort were found in general to be quite comparable to those of 2-15 years old estimated by de Veen (1978). Both measures of fishing effort predicted a relatively high stock levels in the early period and a relatively low stock levels towards the end of the period. The movements of these stock levels are depicted in figure 5.4.

The estimated stocks of species 3 (cod) seemed to agree reasonably well for both measures of fishing efforts, and were generally higher than those estimated by Daan (1978). Both fishing efforts predicted a relatively low stocks at the beginning (e.g 1961) and end (e.g 1974) of the period and maximum stocks of more than 1.4 million metric tons in 1971. These 1971 stocks were reduced to less than 400000 metric tons in 1974. Figure 5.5 shows the closely similar movement of the stock levels predicted by both measures of fishing effort.

For species 4 (haddock), the stocks estimated by the first fishing effort were generally much higher than those estimated by the second fishing effort. However, both predicted a relatively high stock levels in 1966 and 1970. A relatively low stock levels were predicted during the early sixties (1960-1964). As can

be seen from figure 5.6, the patterns exhibited by both estimated stocks are quite similar to one another.

As with species 4, the first fishing effort estimated a higher stock level of species 5 (saithe) than the second fishing effort. Starting with low levels in the early period, the stocks increased steadily, reaching their first peak in 1966. The stocks decreased for the next two years before starting to increase again, reaching their second peak in 1971. Another decrease in the level occured in 1972 before the stocks recovered to reach their third peak at the end of the period (1974/75). These movements are depicted in figure 5.7.

Despite the very fluctuating nature of their estimated levels, the stocks of species 6 (whiting) estimated by both fishing efforts appeared to agree reasonably well with each other. These stock levels were found to be quite comparable to those of 2-8 years old estimated for the early and late sixties (Jones, 1982). Figure 5.8 shows these fluctuating stock levels of species 6 with a slightly higher estimates for those corresponding to the second fishing effort.

With exception of the second year (1961), the estimated stocks of species 7 (herring), one of the main pelagic species, for both fishing efforts showed only slight deviations from each other with a generally higher stock corresponding to the first fishing effort. Both fishing efforts estimated a highest stock level of

well above 4.5 million metric tons in 1964 which is comparable to the highest adult biomass of 2.3 million metric tons estimated for the same year from virtual population analysis (Saville and Bailey, 1980). A severe depletion in the stock level occured in later years reducing it to less than 1 million metric tons in 1968 and the seventies. During this period (1968-1975), the estimated stocks were found to recover to a level of about 2 million metric tons only once, in 1969. A graphical representation is given in figure 5.9.

The estimated stocks of species 8 (sprat), a commercially less important pelagic species, are given in table 5.12 and graphically depicted in figure 5.10. The stock levels estimated by the two fishing efforts showed significant deviations from each other with a higher stock estimated by the first fishing effort. However, the patterns exhibited by both were quite similar — a relatively high stocks in 1964, 1967 and the last three years (1973-1975) and a relatively low stocks in other years. Bailey (1980) estimated the total biomass of sprat stock from virtual population analysis for two different mortality rates, M=0.8 and M=1.2 for the period 1967-1976. Both suggested a relatively high stock level during late sixties (1968/69) and mid-seventies (1974/75/76). Except for the period 1972-1975, the stocks estimated by Bailey were generally higher than those estimated here.

Table 5.13 and figure 5.11 give the estimated

stock of species 9 (mackerel), another commercially important pelagic species after herring. The first fishing effort estimated a much higher stock levels than the second fishing effort. The first estimate suggested a high stock level of more than 14 million metric tons at the beginning of the period and decreasing to about 3.0 million metric tons in 1963 before recovering to about 6.5 million metric tons a year later. The second estimate, however suggested a lower stock level of about 7.5 million metric tons at the beginning of the period and decreasing to about 1.2 million metric tons in 1963 before recovering to about 2.5 million metric tons in 1964. After 1964, both estimates suggested a relatively low stock levels for 1969/70 and a relatively high stocks for 1973. Hamre (1978, 1980) estimated the spawning stock (> 3 years) biomass for the period 1964-1975. The pattern exhibited by his estimates -- a relatively high spawning stock of more than 2.0 million metric tons for the first few years and a relatively low spawning stock of less than 0.5 million metric tons in 1970/71, followed by a recovered spawning stock of more than 1.0 million metric tons in later years — appeared to be quite similar to those exhibited by the stocks estimated here.

Year	B(1) ('000)	BT(1) ('000)	S(1)
1960	872.20	531.80	
1961	752.20	222.30	(1960-1964)
1962	977.90	604.40	635158 (metric tons) per year
1963	1255.10	595.10	
1964	1293.20	611.00	
1965	1253.60	541.20	
1966	1112.30	367.00	(1965-1969)
1967	1173.80	426.00	734817 (metric tons) per year
1968	1080.40	240.90	
1969	1147.20	556.80	
1970	1274.40	609.70	
1971	1038.96	577.00	
1972	981.50	610.90	
1973	772.10	381.10	
1974	90.30	70.90	
1975	163.70	90.00	

Note: B(1) and BT(1) are estimated stocks biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(1) is the stock biomass per year estimated from virtual population analysis (Bannister, 1978)

Table 5.5 Estimated stocks of species 1: Plaice, 1960-1975 (metric tons)

Year	B(2) ('000)	BT(2) ('000)	S(2) ('000)
1960	183.90	793.40	126.00
1961	209.50	438.10	127.00
1962	258.60	1130.80	120.00
1963	308.10	1033.40	101.00
1964	92.50	309.40	109.00
1965	145.80	445.20	136.00
1966	155.10	362.20	145.00
1967	106.20	272.70	151.00
1968	85.30	134.50	137.00
1969	56.70	194.80	110.00
1970	65.20	220.80	100.00
1971	55.10	216.90	99.00
1972	52.70	232.70	90.00
1973	91.40	319.40	85.00
1974	57.40	319.40	
1975	56.00	218.90	

Note: B(2) and BT(2) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(2) are estimated density of 2-15 years old (de Veen, 1978)

Table 5.6 Estimated stock of species 2: C.Sole 1960-1975 (metric tons).

Year	B(3) ('000)	BT(3) ('000)	S(3)
1960	359.00	493.40	(1950-1962)
1961	285.00	190.00	170000 metric
1962	313.70	437.00	tons per year
1963	340.40	363.80	- - - - - - - - - -
1964	381.90	406.70	(1963-1968)
1965	637.00	619.80	392000-457000
1966	869.70	646.90	metric tons
1967	1208.10	988.50	per year
1968	1283.20	644.90	- - - - - - - - - -
1969	910.00	995.50	(1969-1973)
1970	1164.40	1255.70	329000-330000
1971	1431.00	1791.60	metric tons
1972	1052.00	1475.90	per year
1973	754.50	839.90	- - - - - - - - - -
1974	215.00	380.70	
1975	456.80	566.20	

Note: B(3) and BT(3) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(3) are estimated biomass of cod stock during different period (Daan, 1978)

Table 5.7 Estimated stock of species 3: Cod 1960-1975 (metric tons)

Year	B(4) ('000)	BT(4) ('000)	S(4)
1960	313.10	115.20	(1959-1961) 118000 metric tons per year
1961	264.70	47.20	
1962	261.70	97.70	
1963	247.70	70.90	
1964	443.60	126.50	
1965	561.60	146.30	
1966	1457.30	290.10	
1967	951.50	208.40	
1968	548.10	73.70	(1968-1970)
1969	3411.50	999.00	597000 metric tons per year
1970	5778.90	1668.10	
1971	1806.30	605.30	
1972	1008.40	378.70	
1973	1052.50	313.60	
1974	941.10	446.00	
1975	830.80	275.60	

Note: B(4) and BT(4) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(4) are estimated biomass of haddock stock for age group 2-8 years for early and late sixties (Jones, 1982)

Table 5.8 Estimated stock of species 4: Haddock 1960-1975 (metric tons)

Year	B(5) ('000)	BT(5) ('000)	S(5)
			(1960-1962)
1960	211.10	50.80	
1961	155.90	18.20	193000 metric tons per year
1962	184.30	44.90	
1963	216.10	40.40	
1964	226.60	42.20	
1965	371.80	63.30	
1966	1039.80	135.40	
1967	699.00	100.00	
1968	742.20	65.30	(1968-1970)
1969	1411.30	270.30	896000 metric tons per year
1970	2578.00	486.70	
1971	3651.90	800.500	
1972	615.30	680.70	
1973	2878.00	560.90	
1974	5376.70	1666.90	
1975	5872.50	1274.30	

Note: B(5) and BT(5) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(5) are estimated biomass of saithe stock for age group 2-14 years (Jones, 1982).

Table 5.9 Estimated stock of species 5: Saithe

1960-1975 (metric tons)

Year	B(6) ('000)	BT(6) ('000)	S(6)
			(1959-1961)
1960	143.70	271.30	
1961	135.50	123.90	102000 metric tons per year
1962	223.80	428.20	
1963	163.70	240.30	
1964	139.70	204.40	
1965	200.80	268.40	
1966	413.00	421.90	
1967	208.20	234.00	
1968	309.30	213.50	(1968-1970)
1969	232.70	349.70	217000 metric tons per year
1970	340.40	504.30	
1971	184.50	317.30	
1972	197.40	380.40	
1973	193.20	295.50	
1974	168.80	410.60	
1975	194.97	331.90	

Note: B(6) and BT(6) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(6) are biomass of whiting stock for age group 2-8 years (Jones, 1982).

Table 5.10 Estimated stock of species 6: Whiting 1960-1975 (metric tons)

Year	B(7) ('000)	BT(7) ('000)	S(7) ('000)
1960	4086.40	4262.90	2223
1961	3733.70	1887.80	2010
1962	3459.10	3657.60	1597
1963	4669.80	3788.60	1761
1964	5787.10	4678.20	2306
1965	5096.30	3764.00	2105
1966	3912.40	2208.80	1481
1967	2005.40	1245.50	1188
1968	937.10	357.50	889
1969	2174.50	1805.70	518
1970	1591.20	1302.60	551
1971	299.90	285.10	407
1972	634.00	675.20	
1973	1065.20	900.10	
1974	609.10	818.70	
1975	847.30	797.10	

Note: B(7) and BT(7) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(7) are adult biomass estimated from virtual population analysis (Saville and Bailey,1980)

Table 5.11 Estimated stock of species 7: Herring 1960-1975 (metric tons)

Year	B(8) ('000)	BT(8) ('000)	S(8) ('000)	
1960	119.50	46.30		
1961	96.00	18.00		
1962	291.30	114.30		
1963	647.40	194.90		
1964	1384.50	415.50		
1965	510.50	139.90		
1966	332.80	69.70		
			(M=0.8)	(M=1.2)
1967	1009.80	232.70	817	4625
1968	1137.10	161.00	1063	3324
1969	330.50	101.90	1038	1735
1970	488.90	148.60	946	935
1971	428.70	151.30	711	594
1972	1268.30	501.40	484	419
1973	2281.90	715.80	518	680
1974	4217.90	2104.50	859	1260
1975	5097.60	1780.10	1198	1567
1976	(not available)		1154	1697

Note: B(8) and BT(8) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(8) are total biomass of sprat stock estimated from virtual population analysis for two different mortality rates, M (Bailey, 1980).

Table 5.12 Estimated stock of species 8: Sprat

1960-1975 (metric tons)

Year	B(9) ('000)	BT(9) ('000)	S(9) ('000)
1960	14706.20	7567.20	..
1961	14255.60	3555.40	..
1962	13008.90	6785.00	..
1963	3085.90	1234.80	..
1964	6462.70	2576.50	2190
1965	2696.00	982.00	2866
1966	2831.90	788.40	2692
1967	3736.10	1144.20	1913
1968	2973.50	559.40	1468
1969	481.30	197.50	938
1970	763.70	308.10	445
1971	1698.90	796.10	247
1972	1004.70	527.90	1483
1973	6675.90	2782.40	1295
1974	3516.70	2331.30	1099
1975	6370.30	2956.00	839

Note: B(9) and BT(9) are estimated stock biomasses based on fishing efforts measured in hours fishing and ton-hours fishing respectively.

S(9) are the estimated spawning stock (> 3years) biomass (Hamre, 1978, 1980).

Table 5.13 Estimated stock of species 9: Macherel

1960-1975 (metric tons)

Year	B(10) ('000)	BT(10) ('000)
1960	460.60	1193.10
1961	437.80	550.00
1962	446.30	1172.80
1963	702.60	1416.50
1964	720.90	1448.10
1965	675.20	1239.30
1966	603.20	846.20
1967	633.90	978.30
1968	579.50	549.40
1969	663.40	1368.90
1970	660.10	1342.70
1971	809.60	1911.70
1972	2407.10	6370.10
1973	3619.80	7600.90
1974	10380.60	34671.40
1975	8802.20	20577.90

Note: B(10) and BT(10) are estimated stock biomasses based on the fishing efforts measured in hours fishing and ton-hours fishing respectively.

Table 5.14 Estimated stock of species 10: Others 1960-1975 (metric tons)

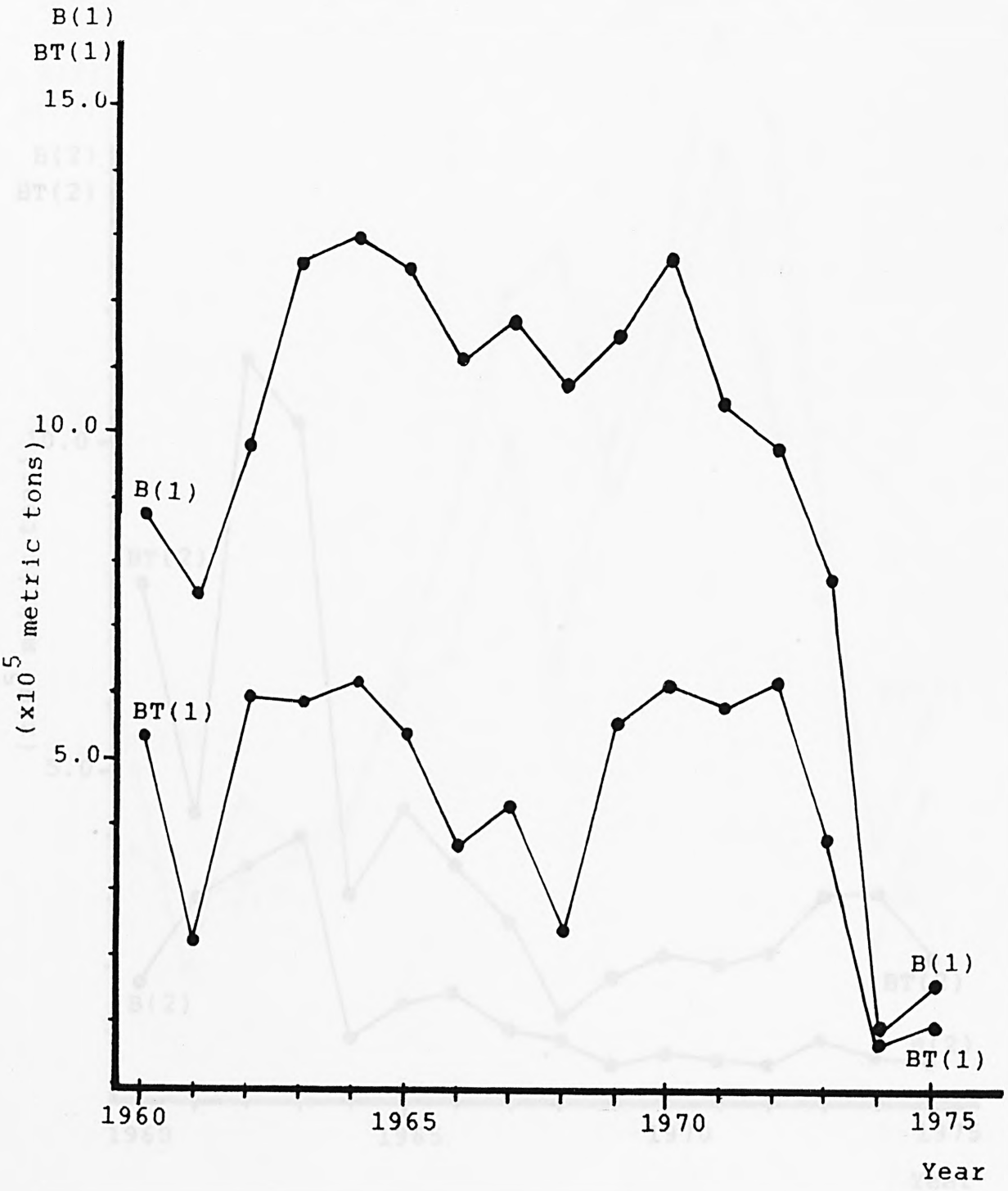


Figure 5.3 Estimated stock of species 1 (Plaice)

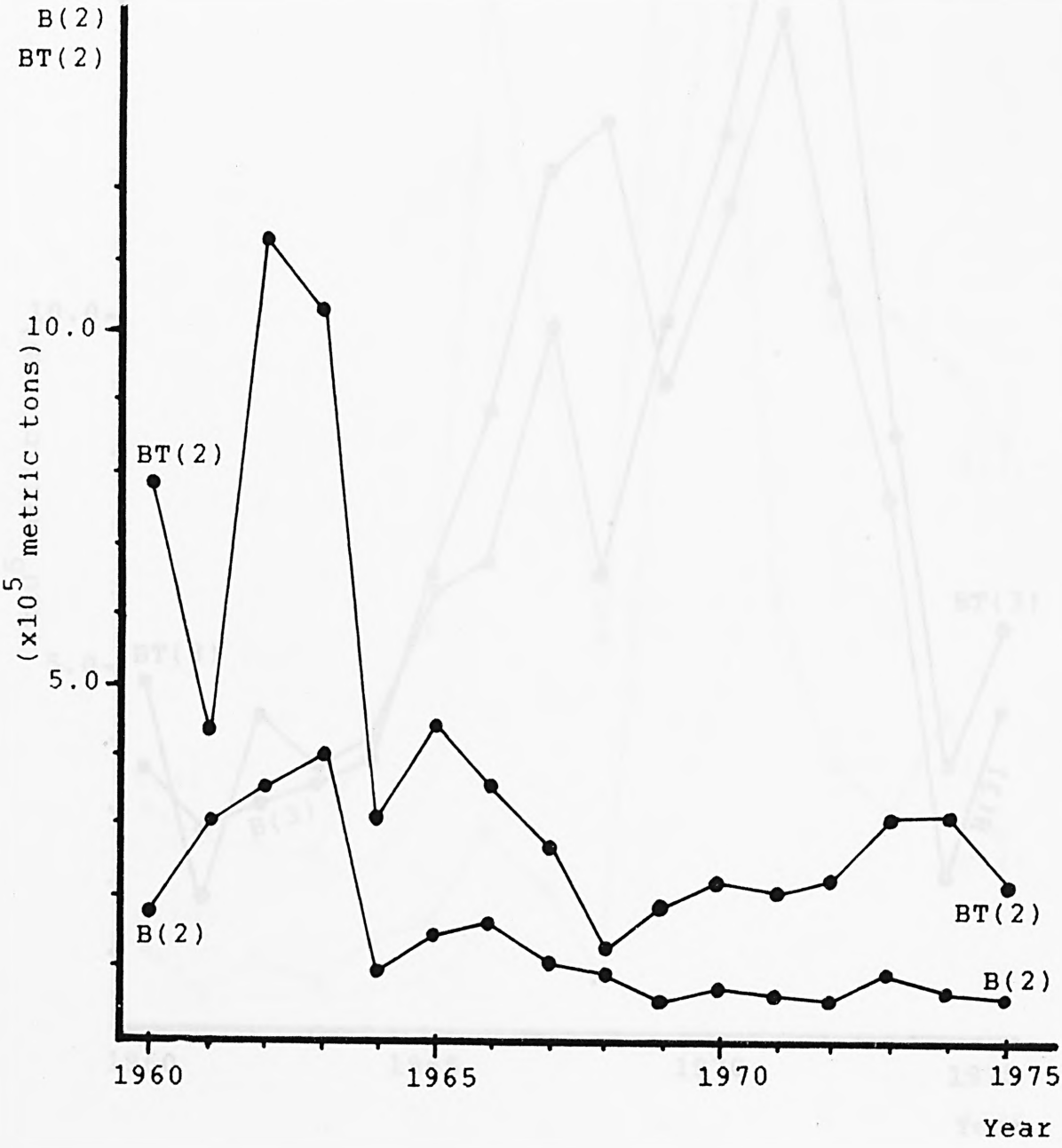


Figure 5.4 Estimated stock of species 2 (C.Sole)

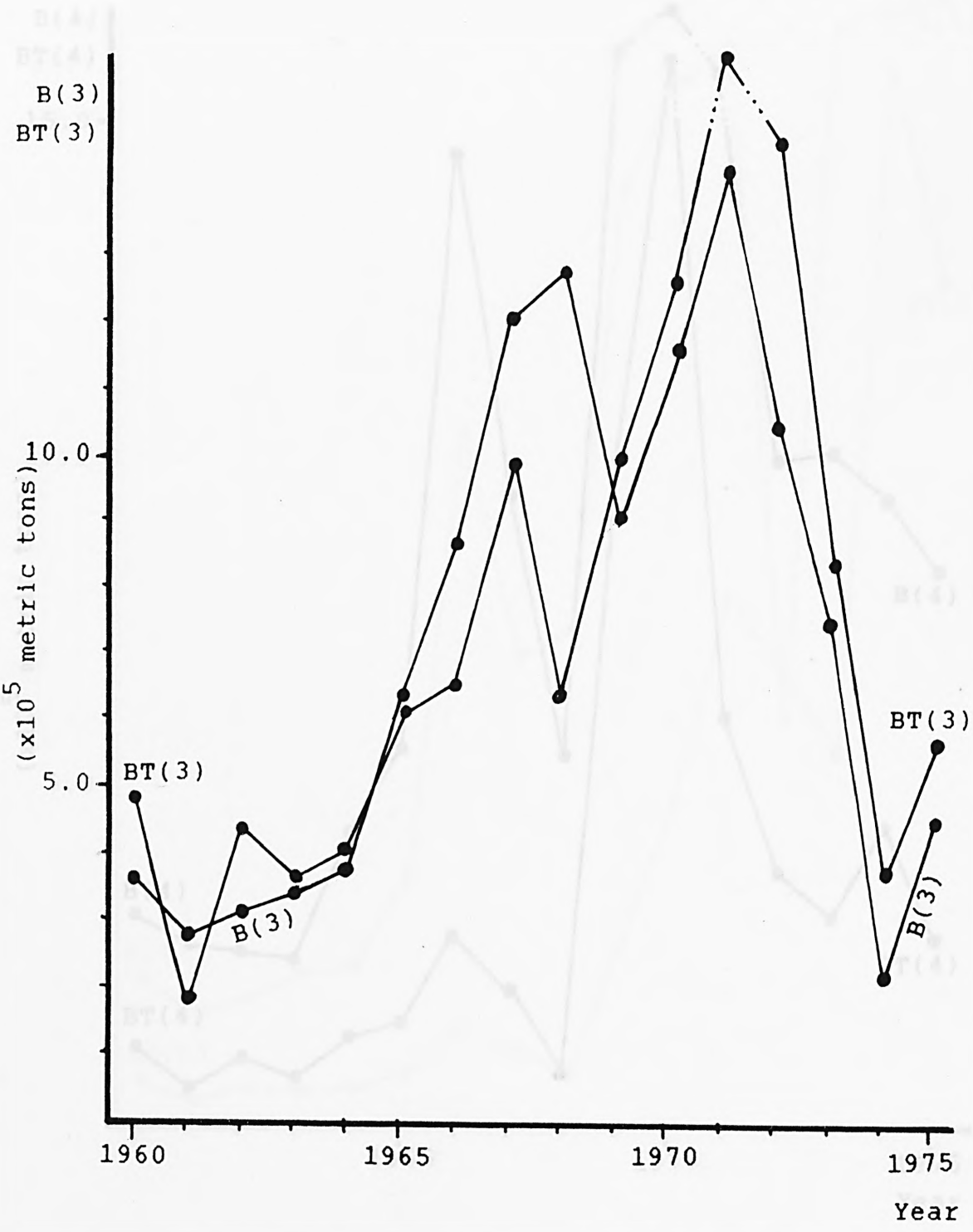


Figure 5.5 Estimated stock of species 3 (Cod)

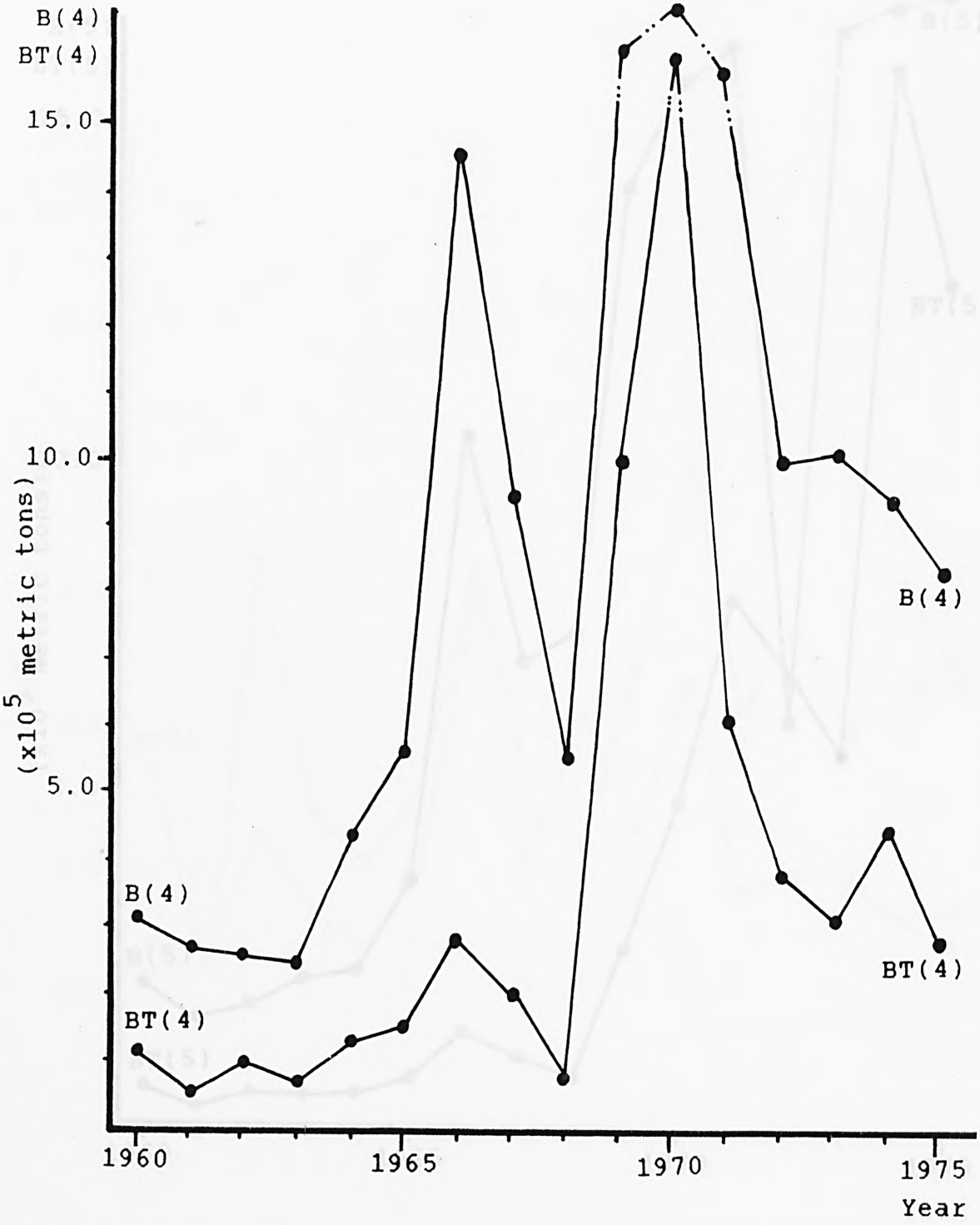


Figure 5.6 Estimated stock of species 4 (Haddock)

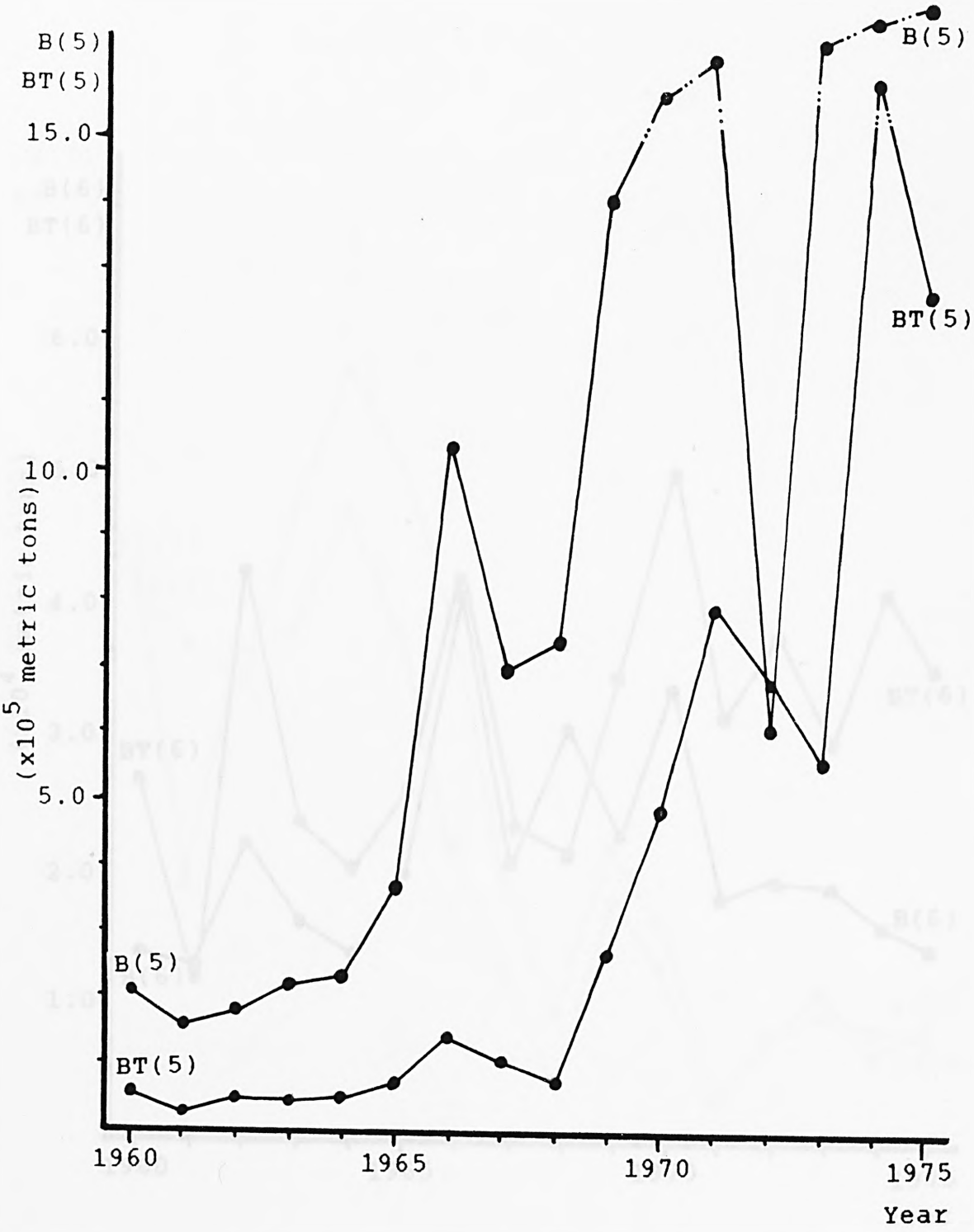


Figure 5.7 Estimated stock of species 5 (Saithe)

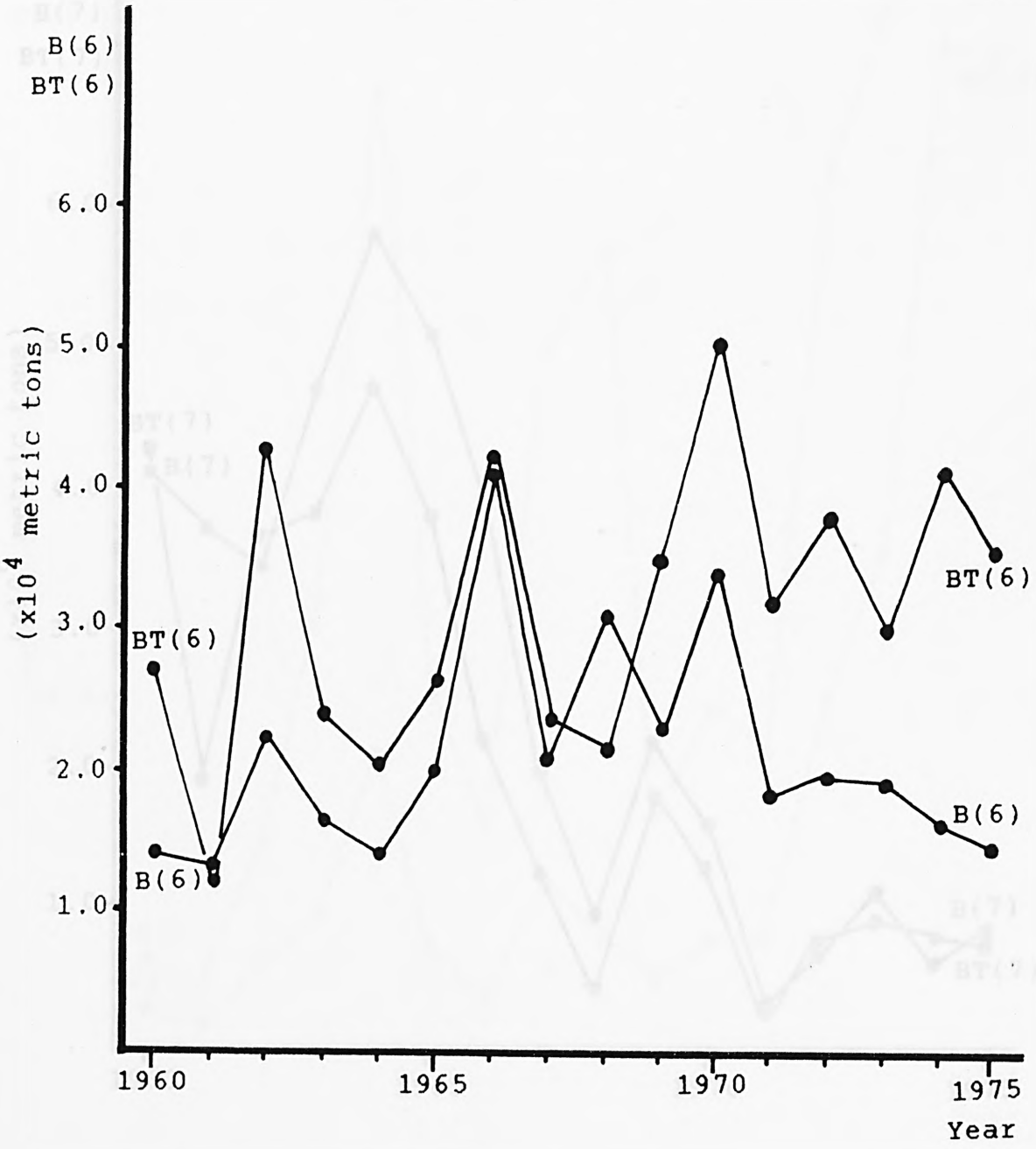


Figure 5.8 Estimated stock of species 6 (Whiting)

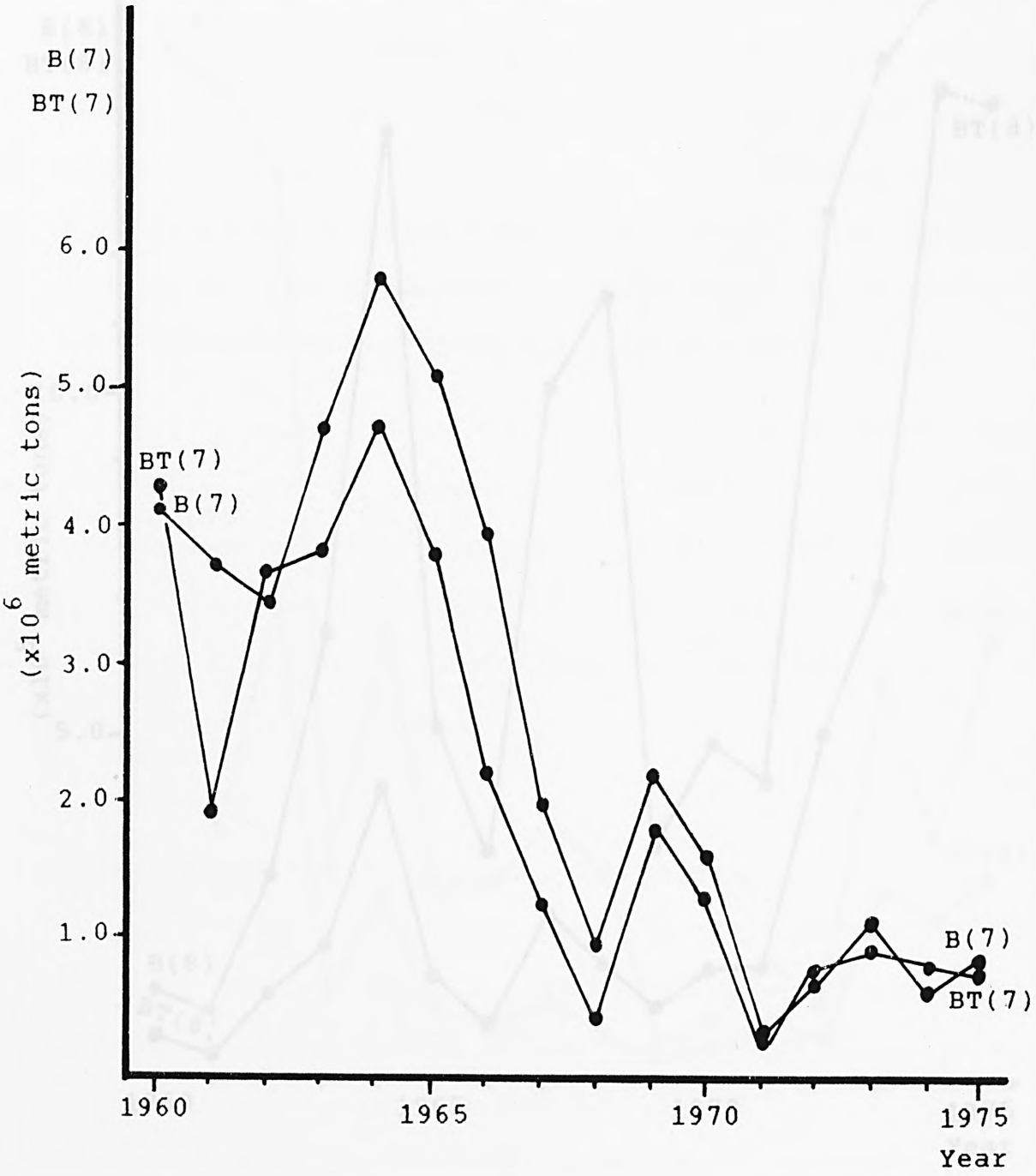


Figure 5.9 Estimated stock of species 7 (Herring)

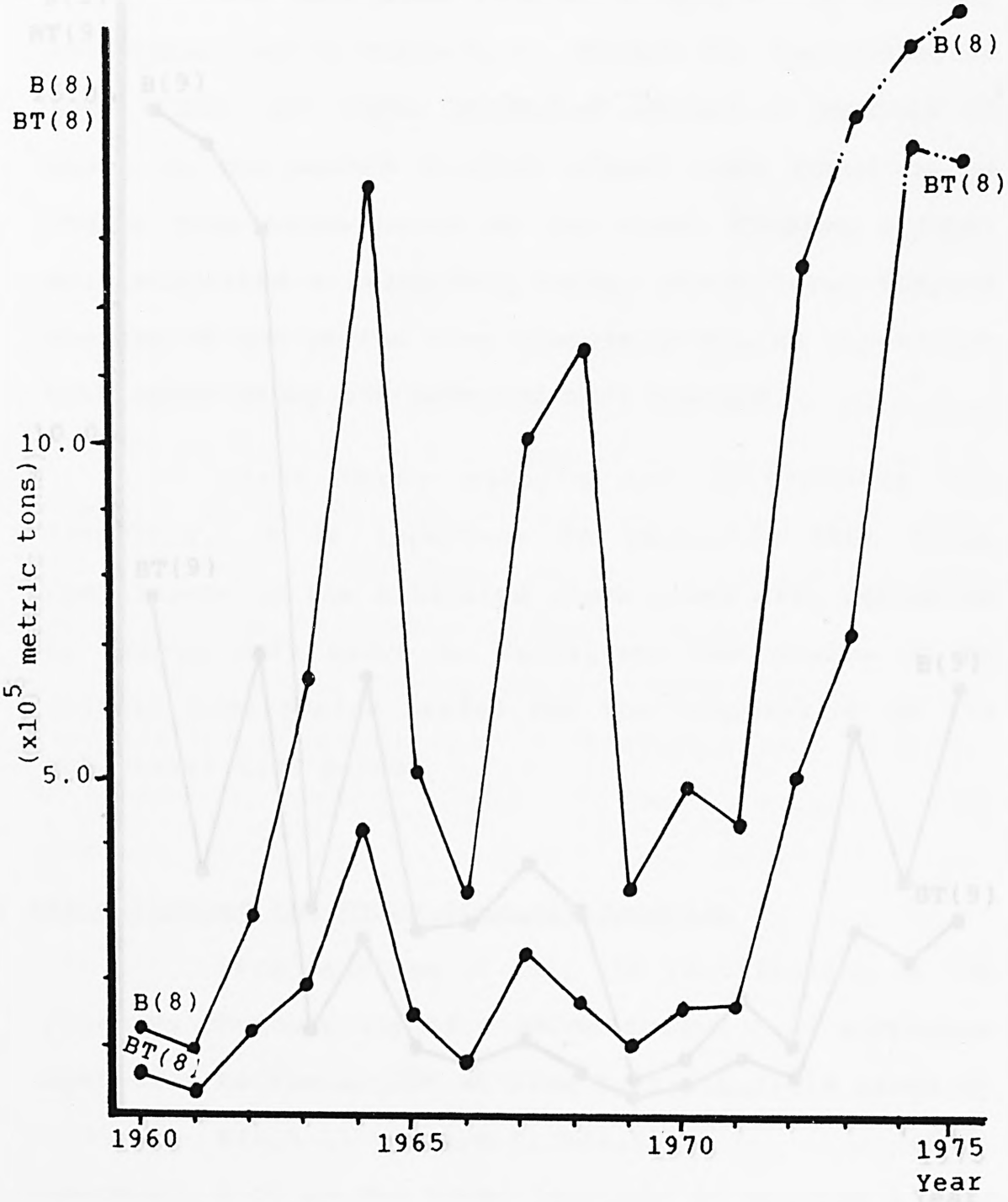


Figure 5.10 Estimated stock of species 8 (Sprat)

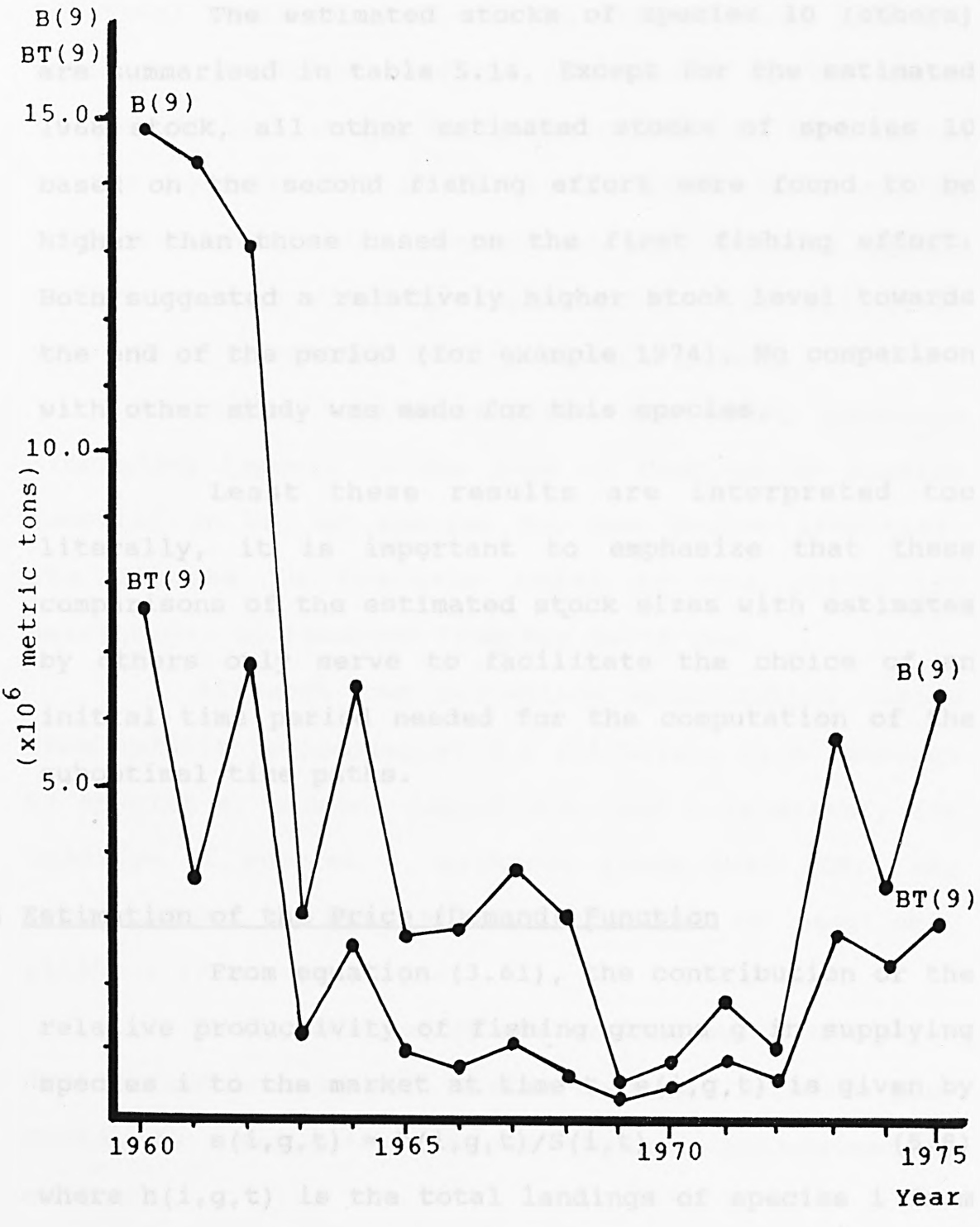


Figure 5.11 Estimated stock of species 9 (Mackerel)

The estimated stocks of species 10 (others) are summarised in table 5.14. Except for the estimated 1968 stock, all other estimated stocks of species 10 based on the second fishing effort were found to be higher than those based on the first fishing effort. Both suggested a relatively higher stock level towards the end of the period (for example 1974). No comparison with other study was made for this species.

Least these results are interpreted too literally, it is important to emphasize that these comparisons of the estimated stock sizes with estimates by others only serve to facilitate the choice of an initial time period needed for the computation of the suboptimal time paths.

5.4 Estimation of the Price (Demand) Function

From equation (3.61), the contribution or the relative productivity of fishing ground g in supplying species i to the market at time t, e(i,g,t) is given by

$$e(i,g,t) = h(i,g,t)/S(i,t), \qquad (5.8)$$

where h(i,g,t) is the total landings of species i from fishing ground g in year t, and S(i,t) is the total supply of species i at time t (this includes the total landings from all fishing grounds and imports of species i).

With reference to the North Sea fishery and for the purpose of our illustration we will consider

the total landings in UK and the contributions from the North Sea to these landings. Being one of the major fishing nations in the North Sea (after the declaration of the 200-mile EEZ in 1977) the trend shown by the British fishery with respect to this fishing ground should be approximately representative of all other major fishing nations fishing on this ground.

Table 5.16 summarises the total landings (including imports in the form of landings by foreign vessels) in UK, by species for the period 1979-1983. The figures in brackets refer to the ratio (or percentage) of landings from the North Sea.

Although the percentage contribution varied from species to species with a relatively high landings of species 4, haddock (about 90%) and a relatively low landings of species 9, mackerel (less than 10%), the trends shown by most species appeared to vary only slightly from year to year.

Thus, to simplify our estimation of the price demand functions we will assume that the relative productivity $e(i,g,t)$ in our case is approximately constant.

The price demand functions can then be written as

$$P(i,t) = p_o(i) + b(i)h(i,t), \quad i=1,\ldots,10 \qquad (5.9)$$

where $P(i,t)$ is the unit price of species i and $h(i,t)$ is the harvest of species i at time t, $p_o(i)$ and $b(i)$ are constants.

	1979	1980	1981	1982	1983
1. PLAICE	35844	29027	27510	27500	26065
	(0.84)	(0.79)	(0.79)	(0.76)	(0.67)
2. C.SOLE	2133	1937	1865	2271	2383
	(0.31)	(0.24)	(0.21)	(0.18)	(0.18)
3. COD	160271	148024	147988	141610	135959
	(0.61)	(0.64)	(0.76)	(0.79)	(0.83)
4. HADDOCK	82542	94664	106864	134371	126989
	(0.79)	(0.81)	(0.91)	(0.92)	(0.91)
5. SAITHE	25330	29326	21814	25742	18419
	(0.57)	(0.39)	(0.50)	(0.53)	(0.71)
6. WHITING	61563	56690	52154	51288	57089
	(0.85)	(0.86)	(0.72)	(0.67)	(0.80)
7. HERRING	4588	5568	36475	48281	54235
	(0.01)	(0.01)	(0.01)	(0.11)	(0.29)
8. SPRAT	25203	24109	27635	19562	10235
	(0.81)	(0.58)	(0.57)	(0.70)	(0.35)
9.MACKEREL	362771	265815	197592	194238	201731
	(0.01)	(0.04)	(0.07)	(0.00)	(0.00)
10. OTHERS	103750	133302	118539	129155	118175
	(0.17)	(0.28)	(0.41)	(0.48)	(0.32)
TOTAL	863995	788462	738436	774018	751467
	(0.35)	(0.40)	(0.49)	(0.50)	(0.48)

Figures in brackets refer to percentage of landings from the North Sea.

Sources: ICES, Bulletin Statistique (various years)
MAFF, Sea Fisheries Statistical Tables (various years).

Table 5.15 Landings in UK, by species, 1979-1983

(metric tons)

The parameters $p_o(i)$ and $b(i)$ for each species $i=1,\ldots,10$, were then estimated by performing linear regressions (by OLSQ method) on the total harvests of each species from the North Sea against the unit price of each species landed in UK expressed in 1975 prices and covering the time period 1960-1983. The results are summarised in Appendix D.

The values of R^2 varied from 0.42 to 0.84. The estimated parameters, $p_o(i)$ and $b(i)$, $i=1,\ldots,10$, all assumed the expected signs (positive $p_o(i)$ and negative $b(i)$) with $b(i)$s assuming relatively small values. This seemed to indicate that the unit price of fish (when expressed in the price of a single year) in general only varies slightly with the harvest.

The system of price demand functions can thus be written as

$$
\begin{aligned}
P(1,t) &= 550.30 - 1.9547(10^{-3})h(1,t)\\
P(2,t) &= 1853.9 - 2.9319(10^{-2})h(2,t)\\
P(3,t) &= 581.35 - 1.1570(10^{-3})h(3,t)\\
P(4,t) &= 301.38 - 2.1854(10^{-4})h(4,t)\\
P(5,t) &= 201.93 - 3.828(10^{-4})h(5,t)\\
P(6,t) &= 168.08 - 2.4624(10^{-4})h(6,t)\\
P(7,t) &= 216.34 - 2.2496(10^{-4})h(7,t)\\
P(8,t) &= 41.473 - 1.9461(10^{-5})h(8,t)\\
P(9,t) &= 69.953 - 5.8782(10^{-5})h(9,t)\\
P(10,t) &= 203.69 - 5.7802(10^{-5})h(10,t).
\end{aligned}
\qquad (5.10)
$$

5.5 Estimation of Revenue and Cost Functions

Multiplying equation (5.10) by h(i,t) yields a system of revenue functions, R(i,t) associated with each species i (=1,...,10). The total revenue generated in year t is thus

$$TR(t) = \sum_i R(i,t)$$
$$= \sum_i P(i,t)h(i,t), \qquad (5.11)$$

where P(i,t), i=1,...,10 are given by equation (5.10).

Tables 5.16 and 5.17 give the total revenue (in monetary value) per thousand of fishing effort for the North Sea catches by species for the time period 1960-1975, for the two measures of fishing effort respectively. These values are based on the 1975 prices of species landed in UK.

The minimum revenues per thousand of fishing effort for each species were noted and taken to be the approximate cost per thousand of fishing effort directed at that species, c(i), i=1,...,10. The years when these minimum averages occured were found to differ from species to species as well as for the two measures of fishing effort (from as early as 1960 for species 8 for fishing effort measured in thousand of ton-hours fishing to as late as 1975 for species 2 for both measures of fishing effort).

Year	Revenue per fishing effort (£/'000HF)(*)				
	Plaice	C.Sole	Cod	Haddock	Saithe
1960	5580.5	5075.8	3014.4	2370.7	391.5
1961	4777.9	6316.3	2468.1	2002.7	284.9
1962	6029.4	8224.9	2727.5	1908.4	324.5
1963	7603.2	10413.0	2966.2	1784.5	371.1
1964	7396.1	3285.7	3370.3	3110.6	378.7
1965	7248.0	5383.1	5643.5	3857.1	615.7
1966	6251.7	5907.4	7715.0	9789.9	1661.8
1967	6483.3	4205.6	10833.5	6235.7	1089.9
1968	5785.2	3447.3	11331.9	3503.4	1113.7
1969	5818.1	2282.6	7814.4	20506.0	1991.6
1970	6080.0	1603.5	9647.8	32871.2	3397.8
1971	5693.6	890.4	16116.6	14768.0	6171.7
1972	5991.8	853.4	21399.0	11839.8	1241.8
1973	4831.0	433.4	11342.0	10294.7	6209.4
1974	552.89	231.7	2666.4	9147.7	13710.4
1975	975.57	219.7	4921.3	6816.5	10041.9

Year	Revenue per fishing effort (£/'000HF)(*)				
	Whiting	Herring	Sprat	Mackerel	Others
1960	972.3	2904.9	31.2	1388.7	2250.3
1961	903.0	2729.0	24.69	1400.1	2139.8
1962	1464.3	2536.9	72.2	1295.5	2101.3
1963	1044.4	3473.6	156.6	314.7	3274.0
1964	884.2	4351.2	325.6	671.9	3269.1
1965	1227.8	3839.1	116.0	283.2	3002.3
1966	2436.9	2844.1	73.0	293.3	2625.7
1967	1220.8	1473.0	216.1	393.5	2692.2
1968	1745.5	685.3	234.2	31.37	2402.4
1969	1235.0	1545.3	64.0	49.63	2586.4
1970	1718.1	1090.3	88.5	76.33	2437.5
1971	1241.9	236.9	83.7	150.0	2914.0
1972	1634.3	573.0	278.5	78.6	8582.6
1973	1727.1	984.8	495.1	445.2	12023.1
1974	1334.8	723.1	991.8	186.9	29518.7
1975	1193.0	871.1	775.2	269.5	21237.5

(*) Based on 1975 price of species landed in UK.

Sources: ICES, Bulletin Statistique (various years)
MAFF, Sea Fisheries Statistical Tables (various years)
CSO, Economic Trends (Ann. Supp), 1987.

Table 5.15 Revenue per fishing effort, 1960-1975

Year	Revenue per fishing effort (£/'000TH) (*)				
	Plaice	C.Sole	Cod	Haddock	Saithe
1960	42.40	38.56	22.90	18.01	2.975
1961	17.59	23.26	9.09	7.38	1.050
1962	46.43	63.34	21.00	14.70	2.500
1963	44.93	61.53	17.53	10.54	2.193
1964	43.54	19.34	19.84	18.31	2.229
1965	38.99	28.96	30.36	20.75	3.312
1966	25.70	24.29	31.72	40.25	6.833
1967	29.32	19.02	49.00	28.20	4.930
1968	16.07	9.58	31.48	9.73	3.094
1969	35.19	13.80	47.26	124.00	1.204
1970	36.25	7.19	57.52	196.00	2.026
1971	39.41	6.16	111.50	102.20	4.272
1972	46.47	6.62	166.00	91.84	9.632
1973	29.73	2.67	69.80	63.36	38.21
1974	5.41	2.27	26.10	89.55	134.20
1975	6.68	1.51	33.72	46.71	68.81

Year	Revenue per fishing effort (£/'000TH) (*)				
	Whiting	Herring	Sprat	Mackerel	Others
1960	7.39	22.07	0.24	10.55	17.10
1961	3.33	10.05	0.91	5.16	7.88
1962	11.28	19.54	0.56	9.98	16.18
1963	6.17	20.52	0.92	1.86	19.35
1964	5.21	25.62	1.92	3.96	19.25
1965	6.60	20.65	0.62	1.52	16.15
1966	10.02	11.69	0.30	1.21	10.80
1967	5.52	6.66	0.98	1.78	12.18
1968	4.85	1.90	0.65	0.87	6.67
1969	7.47	9.35	0.39	0.30	15.64
1970	10.24	6.50	0.53	0.46	14.53
1971	8.60	1.64	0.58	1.04	20.17
1972	12.68	4.44	2.16	0.61	66.57
1973	10.63	6.06	3.05	2.74	73.99
1974	13.07	7.08	9.71	1.83	28.90
1975	8.17	5.97	5.31	1.85	145.50

(*) Based on 1975 price of species landed in UK.

Sources: As in Table 5.16

Table 5.17 Revenue per fishing effort, 1960-1975 (£/'000TH)

Thus, based on equation (3.68) we can then deduce the cost per unit of fishing effort as follows:

Case I: fishing effort in '000HF

$$
\begin{aligned}
c(1) &= £552.89 \\
c(2) &= £219.70 \\
c(3) &= £2468.10 \\
c(4) &= £1784.50 \\
c(5) &= £284.90 \\
c(6) &= £884.20 \\
c(7) &= £236.90 \\
c(8) &= £24.69 \\
c(9) &= £31.37 \\
c(10) &= £2101.30
\end{aligned}
\qquad (5.12)
$$

From equation (3.67), the total fishing cost can then be written as

$$
\begin{aligned}
TC(t) = {} & 552.89E(1,t) + 219.70E(2,t) \\
& + 2468.10E(3,t) + 1784.50E(4,t) \\
& + 284.90E(5,t) + 884.20E(6,t) \\
& + 236.90E(7,t) + 24.69E(8,t) \\
& + 31.37E(9,t) + 2101.30E(10,t) + C_F
\end{aligned}
\qquad (5.13)
$$

where $E(i,t)$, $i=1,\ldots,10$ is the composite fishing effort directed at species i, and C_F is the constant fixed cost.

Case II: fishing effort in '000TH

$$
\begin{aligned}
c(1) &= £5.41 \\
c(2) &= £1.51 \\
c(3) &= £9.09 \\
c(4) &= £7.38 \\
c(5) &= £1.05 \\
c(6) &= £3.33 \\
c(7) &= £1.64 \\
c(8) &= £0.24 \\
c(9) &= £0.30 \\
c(10) &= £6.67 \quad .
\end{aligned}
\tag{5.14}
$$

Equation (3.67) in this case then becomes

$$
\begin{aligned}
TC(t) = {} & 5.41E(1,t) + 1.51E(2,t) + 9.09E(3,t) \\
& + 7.38E(4,t) + 1.05E(5,t) + 3.33E(6,t) \\
& + 1.64E(7,t) + 0.24E(8,t) + 0.30E(9,t) \\
& + 6.67E(10,t) + C_F,
\end{aligned}
\tag{5.15}
$$

where $E(i,t)$, $i=1,\ldots,10$ and C_F are as previously defined.

Comparisons of equations (5.12) and (5.14) suggest that on average the unit cost for the two measures of fishing effort varies by a factor of 100. This is not surprising since, on average, the average GRT of fishing vessels operating in the North Sea were of order 100.

5.6 The Dynamic Optimization Model

Following Chapters 3 and 4, we can now restate the dynamic multispecies optimization problem for the North Sea fishery corresponding to the two measures of fishing efforts adopted in the study as

$$\text{MAXIMIZE} \int_0^\infty e^{-\theta t}\{\sum_i \{P(i,t)h(i,t) - c(i)E(i,t)\} - C_F\}dt \quad (5.16)$$

subject to the constraints

$$\text{(i)}\quad dB(i,t)/dt = \{r(i) + \sum_j a(i,j)B(j,t)\}B(i,t) - h(i,t), \quad i=1,\ldots,10 \quad (5.17)$$

$$\text{(ii)}\quad \begin{aligned} 0 &\leqslant B(i,t) \leqslant B_{max}(i) \\ 0 &\leqslant h(i,t) \leqslant h_{max}(i), \quad i=1,\ldots,10 \end{aligned} \quad (5.18)$$

and the initial conditions $B(i,0)$, $h(i,0)$, $i=1,\ldots,10$, where θ is the discount rate (assumed constant), C_F is a constant fixed cost, and $E(i,t)$, $i=1,\ldots,10$ satisfy the relations

$$h(i,t) = Q(i)E(i,t)B(i,t), \quad i=1,\ldots,10, \quad (5.19)$$

$P(i,t)$, $i=1,\ldots,10$ are the price demand functions as given by equation (3.1), and $r(i)$, $a(i,j)$, $Q(i)$ and $c(i)$ are all as defined earlier and assuming the values estimated for each measure of fishing effort.

The suboptimal solutions to the above optimization model and hence the suboptimal time paths corresponding to the two measures of fishing effort are

determined by applying the optimization technique outlined in Chapter 4. The results of these optimizations and their sensitivities constitute the subject of the next chapter.

CHAPTER 6

COMPUTATION OF SUBOPTIMAL SOLUTIONS

6.1 The Initial-Value Problem

Before we solve the bioeconomic optimization model for the suboptimal solutions it is worth noting that the empirical model employed in the study departs significantly from reality. This is because of the less satisfactory regression results and thus a less satisfactory parameter estimates despite employing real data set from the North Sea commercial fishery. Thus its adoption for the study is more of an attempt to give a quasi-realistic model for application of the optimization technique of Chapter 4 rather than claiming to have solve the North Sea multispecies fishery. Reasons for this shortcoming are numerous, some of which were discussed in the previous chapter.

Furthermore, the absence of any terminal condition and the relaxing of the transversality condition suggest that the solutions obtained are not true optimal but at best only suboptimal.

In section 4.4, it was shown that the dynamic optimization of the present value as given by equation (4.1) reduces to solving an initial-value problem of 2n nonlinear first order ordinary differential equations given by equations (4.45) and (4.46). Using similar notations as before, we can rewrite these equations as

$$dB(i,t)/dt = \{a(i,0)+\sum_{j} a(i,j)B(j,t)\}B(i,t)-h(i,t), \quad i=1,\ldots,10; \tag{6.1}$$

$$dh(i,t)/dt = \{ [\theta - a(i,0) - \sum_{j} a(i,j)B(j,t) - a(i,i)B(i,t)]A(i,t) - \sum_{j\neq i} a(j,i)B(j,t)A(j,t) - \{c(i)/[Q(i)B(i,t)]\}\{a(i,0) + \sum_{j} a(i,j)B(i,t)\}\}/[2b(i)], \quad i=1,..,10, \tag{6.2}$$

where

$$A(i,t) = p_o(i)+2b(i)h(i,t)-c(i)/[Q(i)B(i,t)]. \tag{6.3}$$

The computation of the suboptimal policy using the above system of ordinary differential equations requires an estimated initial values for the state and control variables, B(i,t) and h(i,t) at some initial time, t_o. Inspection of tables 5.5 to 5.14 suggests that the estimated stocks of most species for year 1972 agreed reasonably well with those estimated by others for both measures of fishing effort. Therefore, the estimated stocks for 1972 together with their respective harvests will be used as the estimated initial values of the state and control variables in computing their respective suboptimal time paths.

Thus we can write the initial values as

$$\begin{aligned} B(1,0) &= 981500, & B(2,0) &= 52700, \\ B(3,0) &= 1052000, & B(4,0) &= 1008400, \\ B(5,0) &= 615300, & B(6,0) &= 197400, \\ B(7,0) &= 634000, & B(8,0) &= 1268300, \\ B(9,0) &= 1004700, & B(10,0) &= 2407100, \end{aligned} \tag{6.4}$$

for the case where fishing effort is measured in thousand hours fishing;

$$\begin{aligned} B(1,0) &= 610900, \quad B(2,0) = 232700, \\ B(3,0) &= 1475900, \quad B(4,0) = 378700, \\ B(5,0) &= 151000, \quad B(6,0) = 380400, \\ B(7,0) &= 675200, \quad B(8,0) = 501400, \\ B(9,0) &= 527900, \quad B(10,0) = 6370100, \end{aligned} \tag{6.5}$$

for the case where fishing effort is measured in thousand ton-hours fishing; and

$$\begin{aligned} h(1,0) &= 123200, \quad h(2,0) = 21100, \\ h(3,0) &= 346300, \quad h(4,0) = 231200, \\ h(5,0) &= 198600, \quad h(6,0) = 108800, \\ h(7,0) &= 608300, \quad h(8,0) = 92400, \\ h(9,0) &= 182200, \quad h(10,0) = 1019900, \end{aligned} \tag{6.6}$$

for both measures of fishing effort.

The initial-value problem was then solved by applying the Runge-Kutta method of order four with step size 0.01 for time period from 0 to 30 years using a program written in FOTRAN 77. This time period can be extended infinitely. The choice of T=30 years was taken for the purpose of presentation only since by then the pattern of most of the suboptimal paths appeared to be quite established. No condition was imposed at T=30 and the fishery was allowed to continue beyond T=30. Should a terminating condition be imposed at T=30 (for example for a finite time horizon) the suboptimal policy will then be such that the economic profit at T=30 is maximum regardless of performances in other time periods.

The present value,

$$PV = \int_0^{\infty} e^{-\theta t}.Z(\mathbf{B}(t),\mathbf{h}(t))dt, \qquad (6.7)$$

was also computed using Simpson's 1/3 Rule with step size 0.01 and taking the upper limit of integration as 500 years which seems a sufficiently large upper time limit in view of the excessive computing time involved. Furthermore, as the upper limit of integration increases, the contribution to the computed net present value decreases since $e^{-\theta t}$ becomes relatively small as t becomes relatively large.

The results for both measures of fishing effort and their respective sensitivity tests with respect to changes in discount rate, unit price of harvest and unit cost of harvesting where applicable are summarised below. Unless otherwise stated, all the monetary values are in 1975 prices.

6.2 The Case of No Constraint

The initial-value problem with parameters a(i,j), Q(i), $p_o(i)$, b(i) and c(i) assuming values estimated in Chapter 5 and B(i,t) and h(i,t) assuming their appropriate initial values, was numerically solved without being subjected to any biological or economic constraint. These initial solutions for each measure of fishing effort at selected times are summarised in tables 6.1 and 6.2 respectively.

	T=0.0	T=1.0	T=2.0	T=3.0
BIO(1)	981500	1674460	-5.7896E74	-1.6163E75
HAR(1)	123200	128744	-2.2917E74	-6.2721E74
BIO(2)	52700	38854	2.4123E74	7.4782E74
HAR(2)	21100	80835	-3.6185E73	7.2370E73
BIO(3)	1052000	3174870	2.4123E73	2.4123E73
HAR(3)	346300	369589	2.4123E74	5.6690E74
BIO(4)	1008400	3132070	-7.4782E74	-1.9540E75
HAR(4)	231200	-1415850	1.2062E73	-2.1711E74
BIO(5)	615300	2280660	-4.5901E58	-1.0475E59
HAR(5)	198600	151406	-4.8247E73	7.2370E73
BIO(6)	197400	32460	-4.9824E58	-1.4241E59
HAR(6)	108800	-422127	-7.5325E58	-1.8093E74
BIO(7)	634000	226892	7.4782E74	1.9540E75
HAR(7)	608300	145716	-2.4123E74	-1.5680E74
BIO(8)	1268300	11419900	7.4782E74	1.9540E75
HAR(8)	92400	-14715300	7.2370E75	4.8247E73
BIO(9)	1004700	79033	-4.1586E58	-1.0043E59
HAR(9)	182200	-1128170	-3.6185E73	-2.6536E74
BIO(10)	2407100	1892420	4.1010E74	1.4474E75
HAR(10)	1019900	7168400	8.4432E73	1.3268E74

Notes:

1. BIO(i) and HAR(i), i=1,..,10 refer to the biomass and harvest respectively.

2. The term aEn implies a x 10^n.

Table 6.1 Suboptimal solutions : The Case of No Constraint.

(Fishing Effort in '000HF)

	T=0.0	T=1.0	T=2.0
BIO(1)	610900	-3.884E58	-9.769E58
HAR(1)	123200	-6.031E73	-6.031E73
BIO(2)	232700	-9.141E58	-1.503E59
HAR(2)	21100	3.793E74	9.770E74
BIO(3)	1475900	-7.478E74	-1.954E75
HAR(3)	346300	4.825E73	4.825E73
BIO(4)	378700	-7.719E74	-1.978E75
HAR(4)	231200	6.031E73	6.031E73
BIO(5)	151000	-7.237E74	-1.930E75
HAR(5)	198600	3.619E74	9.649E74
BIO(6)	380400	-1.194E73	-1.194E73
HAR(6)	108800	2.412E73	2.412E73
BIO(7)	675200	-7.478E74	-1.954E75
HAR(7)	608300	7.237E73	7.237E73
BIO(8)	501400	-5.066E74	-1.713E75
HAR(8)	92400	4.829E73	4.829E73
BIO(9)	527900	-7.478E74	-1.954E75
HAR(9)	182200	-2.774E74	-8.805E74
BIO(10)	6370100	-3.302E61	-3.307E61
HAR(10)	1019900	-1.327E74	-1.327E74

Notes: (As in Table 6.1)

Table 6.2 Suboptimal Solutions : The Case of No Constraint

(Fishing Effort in '000TH)

For the case of fishing effort measured in thousands of hours fishing (table 6.1) the solutions were found to diverge extensively in both directions (positive and negative) after time t = 2.0 years. In most cases, the solutions appeared to be of order 10^{74} — an unrealistically large magnitude. At the same time some of the solutions were also negative which is unfeasible and violating the nonnegativity constraints.

A similar pattern of solutions were obtained when thousands of ton-hours fishing was used as a measure of fishing effort. However, the divergence occured at an earlier time of t = 1 year (table 6.2).

Thus, some numerical constraints, biological as well as economic, need to be properly formulated and incorporated into the model if the final solutions obtained were to have any meaning within the context of the framework developed in the study.

6.3 The Case of Lower Constraints Only

First we look at the nonnegativity constraints. Since negative biomass has no meaning here, a constraint must be imposed such that whenever the solution implies a negative biomass, the biomass should then be set to zero. Also, whenever this happens, the corresponding harvest should also be set to zero since a zero stock can only produce a zero harvest. Thus we have a constraint of the form

$$\begin{aligned} &\text{if } B(i) < 0.0, \text{ then} \\ &\quad B(i) = 0.0 \\ &\text{and } h(i) = 0.0, \quad i=1,\ldots,10. \end{aligned} \tag{6.8}$$

Negative harvest on the other hand is usually regarded as equivalent to 'investment', at least in principle. Thus a negative harvest would simply imply that more of the stock should be 'invested'. In other words, efforts should be directed at building up the fish stocks. However, in practice the only possible way of doing this is to cease fishing and hopefully it will result in the recovering of the stock if it is not yet severely depleted. This implies a nonnegativity constraint on the harvest of the form

$$\begin{aligned} &\text{if } h(i) < 0.0, \text{ then} \\ &\quad h(i) = 0.0, \quad i=1,\ldots,10. \end{aligned} \tag{6.9}$$

The above lower constraints were then incorporated into the simulation. The suboptimal solutions subjected to these lower constraints for the two measures of fishing efforts at selected times are given in tables 6.3 and 6.4 respectively.

Although the solutions generated appear to be approaching stability, the suboptimal harvests for some species during some time periods were greater (and some were in fact very much greater) than their corresponding biomasses. As a consequence of this unfeasible policy, most of the species were quickly eliminated and zero fishing prevailed after a relatively short time.

	T=1.0	T=6.0	T=9.0
BIO(1)	1652870	8223970	4540570
HAR(1)	137711	212082	660454
BIO(2)	46525	1342740	0.00
HAR(2)	47377	10122500	0.00
BIO(3)	3127090	7017000	984130
HAR(3)	377458	2811820	2703860
BIO(4)	2831960	0.00	0.00
HAR(4)	0.00	0.00	0.00
BIO(5)	2374620	0.0247	0.00
HAR(5)	250731	0.00	0.00
BIO(6)	1972	0.00	0.00
HAR(6)	0.00	0.00	0.00
BIO(7)	183447	250681	0.00
HAR(7)	158913	0.00	0.00
BIO(8)	8832990	26868100	4633240
HAR(8)	0.00	0.00	0.00
BIO(9)	21599	0.00	0.00
HAR(9)	0.00	0.00	0.00
BIO(10)	2958250	0.00	0.00
HAR(10)	1879680	0.00	0.00

Note: BIO(i) and HAR(i), i=1,..,n are as in Table 6.1.

Table 6.3 Suboptimal Solutions : The Case of Lower Constraints Only

(Fishing Effort in '000HF)

	T=0.25	T=0.50	T=0.75	T=4.0
BIO(1)	804443	902758	1088150	5085790
HAR(1)	0.00	0.00	19695	0.00
BIO(2)	176744	0.00	0.00	0.00
HAR(2)	66505	0.00	0.00	0.00
BIO(3)	1327410	0.00	0.00	0.00
HAR(3)	1751110	0.00	0.00	0.00
BIO(4)	189602	0.00	0.00	0.00
HAR(4)	5463950	0.00	0.00	0.00
BIO(5)	110668	0.00	0.00	0.00
HAR(5)	157485	0.00	0.00	0.00
BIO(6)	606424	0.00	0.00	0.00
HAR(6)	4716470	0.00	0.00	0.00
BIO(7)	4591720	0.00	0.00	0.00
HAR(7)	8474500	0.00	0.00	0.00
BIO(8)	0.00	0.00	0.00	0.00
HAR(8)	0.00	0.00	0.00	0.00
BIO(9)	1925400	19528000	0.00	0.00
HAR(9)	376842	458033000	0.00	0.00
BIO(10)	2909200	2594500	3509100	7997600
HAR(10)	0.00	0.00	292460	0.00

Note: BIO(i) and HAR(i) are as in Table 6.1

Table 6.4 Suboptimal Solutions : The Case of Lower Constraints Only.
(Fishing Effort in '000TH)

In table 6.3 where fishing effort is measured in thousands of hours fishing, only three species — species 1, species 3 and species 8 — remained after time t = 9 years. Of these three, only two were subjected to harvesting, one of which at an annual rate greater than the predicted biomass. In the case of the second measure of fishing effort (table 6.4), the depletion of species occured at a much earlier time. At t = 0.75 year, only two species — species 1 and species 10 — remained to generate a positive total harvest of about 312000 metric tons from a combined stock of about 4.6 million metric tons. After t = 4.0 years, the suboptimal policy calls for zero fishing although the total stock size remains above 13.0 million metric tons.

It thus appears that some upper constraints might be needed if the solutions were to be of any interest, with the harvests in each period kept at some levels not exceeding their respective stock sizes. This might also reduce the possibility of depleting the stocks of some species at a relatively early period.

6.4 The Upper Constraints

Since the upper constraint on the state variable, the biomass is subjected to the environmental as well as biological fluctuations which are more often than not beyond our direct control, we will relax the upper constraint on the biomass and let nature dictates

its own course.

Turning to the control variables, h(i), i=1,...,10, an upper constraint seems possible. Consider the profit function for species i(=1,...,10),

$$Z(i) = P(i)h(i) - c(i)E(i) \qquad (6.10)$$

where

$$P(i) = p_o(i) + b(i)h(i), \quad b(i)<0 \qquad (6.11)$$

$$h(i) = Q(i)E(i)B(i), \qquad (6.12)$$

and assuming a zero fixed cost. All the parameters are as defined in the previous chapters (the suffix t is dropped for simplicity).

Elimination of E(i) gives

$$Z(i) = \{[p_o(i)-c(i)/[Q(i)B(i)]+b(i)h(i)]\}h(i) \qquad (6.13)$$

which is quadratic in h(i). The total profit is of course $\sum_i Z(i)$. The graph of Z(i) as a function of h(i) for different levels of B(i) is depicted in figure 6.1. The higher is the level of the biomass B(i), the higher is the shift in the curve Z(i) for a given harvest h(i). This is so since higher level of biomass implies a lower unit cost of harvesting and thus a higher profit. This is reflected in an increasing profit curve such that $Z_{j+1}(i) > Z_j(i)$ for $B_{j+1}(i) > B_j(i)$ where $Z_j(i)$ is the profit curve for the given biomass level $B_j(i)$, j=1,...,4.

Now consider an open-access bioeconomic equilibrium level where the economic rent is completely dissipated. As discussed in Chapter 2, this long run

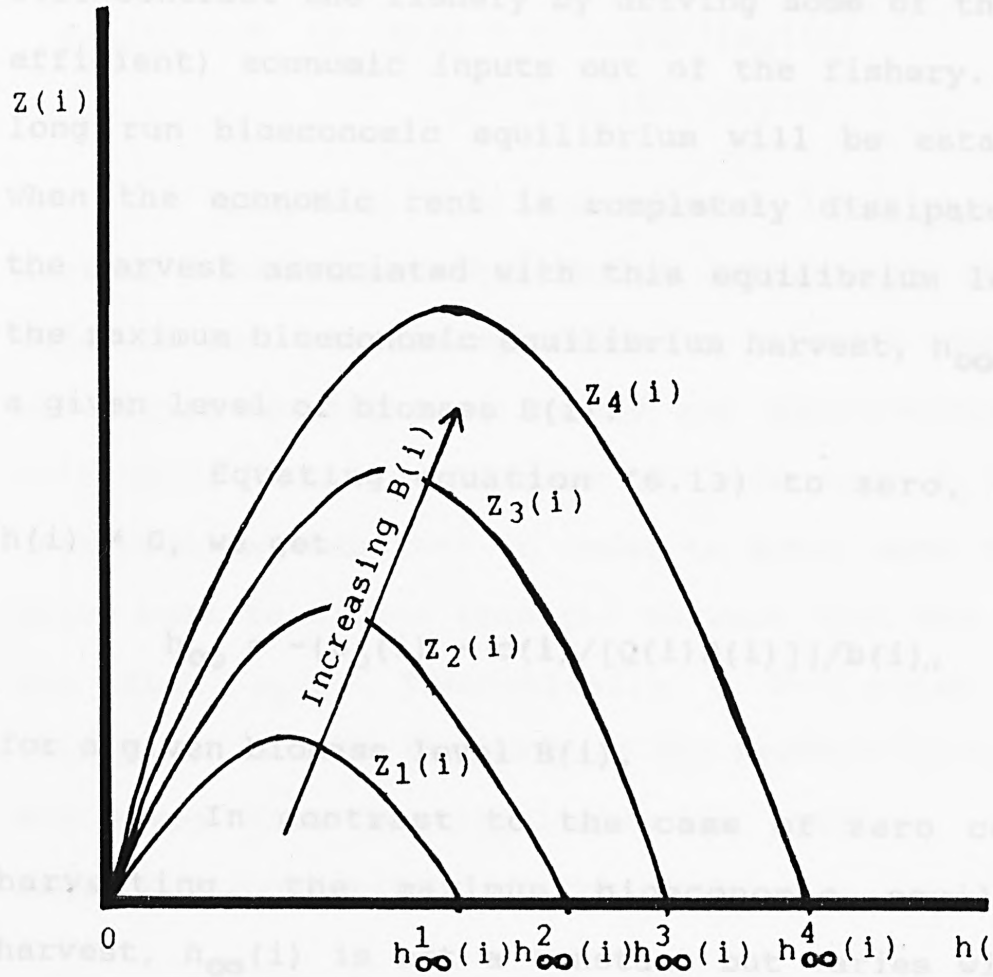


Figure 6.1 Graph of Z(i) as a function of h(i)

equilibrium is reached since the existence of positive economic rent will expand the fishery by attracting in more economic inputs (e.g fishermen, fishing vessels, etc) into the fishery, while a negative economic rent will contract the fishery by driving some of the (less efficient) economic inputs out of the fishery. Thus a long run bioeconomic equilibrium will be established when the economic rent is completely dissipated. And the harvest associated with this equilibrium level is the maximum bioeconomic equilibrium harvest, $h_{\infty}(i)$ for a given level of biomass B(i).

Equating equation (6.13) to zero, and for $h(i) \neq 0$, we get

$$h_{\infty} = -\{p_o(i) - c(i)/[Q(i)B(i)]\}/b(i), \quad (6.14)$$

for a given biomass level B(i).

In contrast to the case of zero cost of harvesting, the maximum bioeconomic equilibrium harvest, $h_{\infty}(i)$ is not a constant but varies with the biomass. Increases in B(i) will induce corresponding increases in $h_{\infty}(i)$. Also,

$$h_{\infty}(i) \rightarrow -p_o(i)/b(i), \text{ as } B(i) \rightarrow \infty. \quad (6.15)$$

The expression $-p_o(i)/b(i)$ is the solution of equation (6.11) when the unit price of harvest, P(i) is zero. Thus equation (6.15) implies that as the biomass increases (infinitely), the maximum bioeconomic equilibrium harvest, $h_{\infty}(i)$ approaches the harvest level

associated with zero unit price. The unit cost of harvesting in this situation is theoretically zero and for zero profit, the unit price should also be zero.

Equation (6.14) also implies that

$$h_{\infty}(i) < 0 \quad \text{if} \quad B(i) < c(i)/[Q(i)p_o(i)] \qquad (6.16)$$
$$= B_o(i), \text{ say.}$$

Thus for some low biomass level $B_o(i)$, the maximum bioeconomic equilibrium harvest is negative. This is not surprising since as biomass decreases, harvesting becomes more costly and thus increases the unit cost. When the biomass is less than $B_o(i)$, the unit cost is such that in order to break even the unit price must be higher than the maximum that the harvest can fetch, $p_o(i)$. Theoretically, a unit price greater than $p_o(i)$ is only possible if the harvest is negative. And since this is unrealistic in practice, we then require a constraint of the form

$$\text{if } h_{\infty}(i) < 0.0 \text{ then} \qquad (6.17)$$
$$h_{\infty}(i) = 0.0, \quad i=1,\ldots,10,$$

on the maximum bioeconomic equilibrium harvest, $h_{\infty}(i)$.

The graph of $h_{\infty}(i)$ as a function of $B(i)$ is depicted in figure 6.2 for cases where $h_{\infty}(i) > B(i)$ in some interval, and $h_{\infty}(i) < B(i)$ in all intervals where $h_{\infty}(i) > 0$.

The case of $h_{\infty}(i) > B(i)$ corresponds to a situation where the unit cost of harvesting is

relatively high (due to a low biomass level) and in order to break even a harvest exceeding the available biomass is required. This is of course not feasible, and a sensible response would be not to harvest, thus giving a constraint of the form

$$\begin{aligned} &\text{if} \quad h_{\infty}(i) > B(i), \quad \text{then} \\ &\qquad h(i) = 0.0, \quad i=1,\ldots,10. \end{aligned} \tag{6.18}$$

Hence assuming that the fishery will in the long run reached the bioeconomic equilibrium level, we can then state the upper constraint on the harvest as

$$\begin{aligned} &\text{if} \quad B(i) \neq 0.0, \text{ and} \\ &\qquad h(i) > h_{\infty}(i), \\ &\text{then} \quad h(i) = h_{\infty}(i), \quad i=1,\ldots,10. \end{aligned} \tag{6.19}$$

Observe that we do not need a constraint of the form

$$\text{if } B(i) = 0.0 \quad \text{then} \quad h_{\infty}(i) = 0.0, \tag{6.20}$$

since equation (6.16) and figure 6.2 imply that whenever $B(i)$ is less than $B_0(i)$ (>0), $h_{\infty}(i)$ is less than zero and constraint (6.17) automatically sets $h_{\infty}(i)$ to zero. In other words, $h_{\infty}(i) \rightarrow 0$ before $B(i) \rightarrow 0$.

Now, from the analysis of single species of Chapter 2, we seen that for a linear case of constant unit price, the open-access bioeconomic equilibrium level is equivalent to the case of an infinite discount rate.

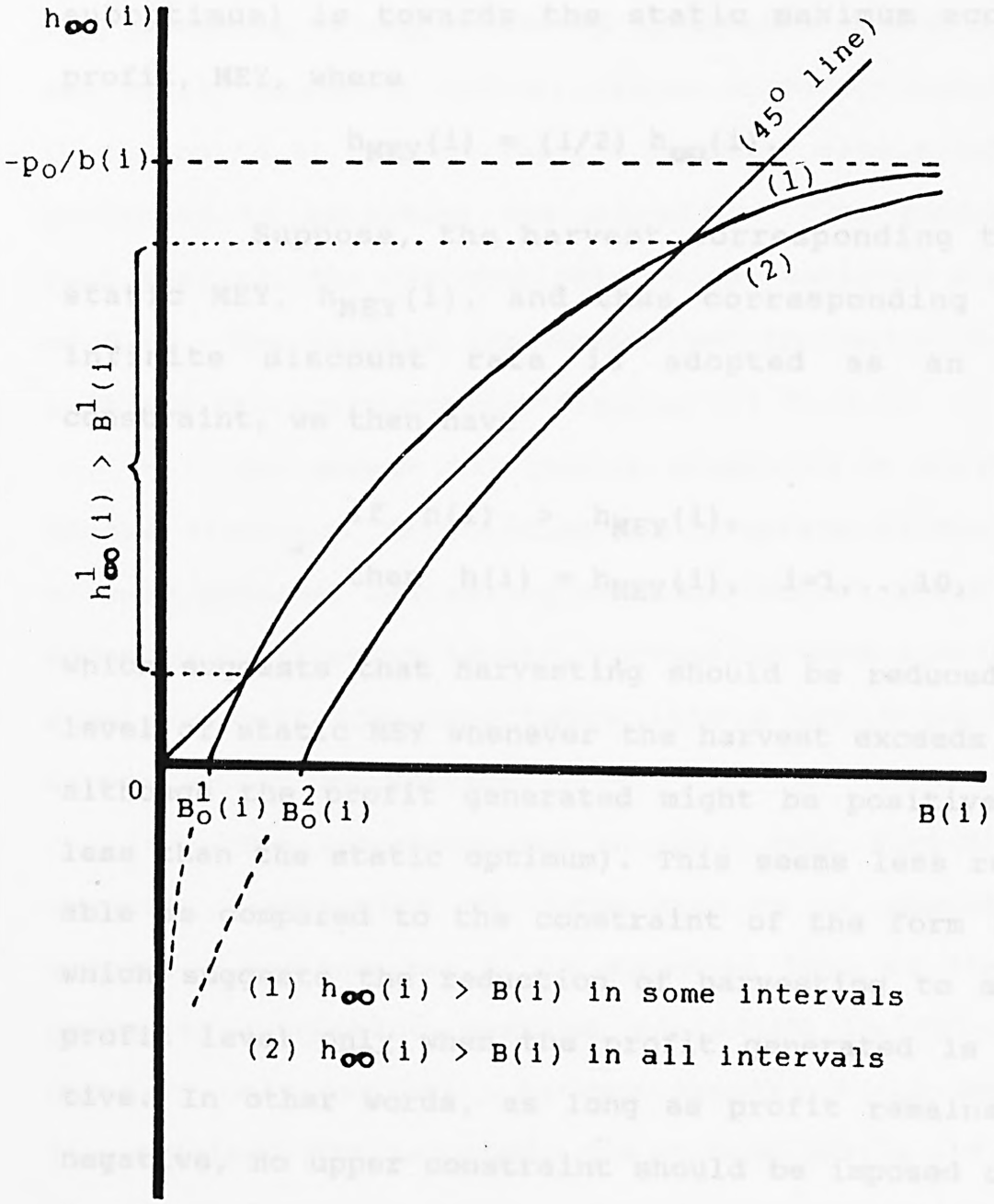


Figure 6.2 Graph of $h_{\infty}(i)$ as a function of B(i)

However, for the nonlinear case of variable unit price adopted in the study, this is not so. For infinite discounting, the tendency for the optimum (or suboptimum) is towards the static maximum economic profit, MEY, where

$$h_{MEY}(i) = (1/2)\, h_{\infty}(i). \qquad (6.21)$$

Suppose, the harvest corresponding to the static MEY, $h_{MEY}(i)$, and thus corresponding to an infinite discount rate is adopted as an upper constraint, we then have

$$\begin{aligned} &\text{if } h(i) > h_{MEY}(i), \\ &\text{then } h(i) = h_{MEY}(i), \quad i=1,..,10, \end{aligned} \qquad (6.22)$$

which suggests that harvesting should be reduced to a level of static MEY whenever the harvest exceeds h_{MEY}, although the profit generated might be positive (but less than the static optimum). This seems less reasonable as compared to the constraint of the form (6.19) which suggests the reduction of harvesting to a zero profit level only when the profit generated is negative. In other words, as long as profit remains non-negative, no upper constraint should be imposed on the harvest.

Furthermore, since (from equation (6.21))

$$\begin{aligned} h_{\infty}(i) &= 2\, h_{MEY}(i), \\ &> h_{MEY}(i), \end{aligned} \qquad (6.23)$$

the imposition of $h_{\infty}(i)$ as an upper constraint on harvest does not seem unreasonable.

6.5 The Constrained Case: Fishing Effort in '000HF

6.5.1 The Suboptimal Time Paths

With parameters a(i,j), Q(i), $p_o(i)$, b(i) and c(i) assuming values estimated in Chapter 5 and B(i,t) and h(i,t) assuming initial values given by equations (6.4) and (6.6) respectively, a computer simulation was performed to determine the suboptimal time paths for each species. The discount rate, θ was assigned a value of 7.5%. The results are summarised in tables 6.5 to 6.14 and the corresponding figures 6.3 to 6.12.

The suboptimal policy suggested a variation in the strategy. This included a complete elimination of some species, harvesting some species at their bio-economic equilibrium levels, harvesting some species at some economically profitable levels and a periodic harvesting of one species.

The suboptimality in this case suggested a complete elimination of three species — species 6, species 7 and species 9. It appeared that of the ten pairs of competing species predicted in the last chapter, only one pair, between species 4 and species 10, remained uneliminated. The suboptimality in this case thus seemed to suggest the eliminations of one or more of the competing species. In addition, species 6 which was one of the first to be eliminated was also being preyed by most of other species, for example species 1, species 3, species 4 and species 8.

Three of the fisheries associated with species 1, species 3 and species 8 should be operated at their bioeconomic equilibrium levels with dissipation of economic rents. Table 6.15, however suggests that their respective profits were non-zero. These were largely due to the rounding off error encountered during the simulations. In fact, the unit profit generated per metric ton of harvest was about -6 pence (a loss of about 6 pence per metric ton) for species 1, 3 pence for species 3, and -0.3 pence (i.e a loss of less than half pence per metric ton) for species 8. Thus, without loss of generality, we can say that the suboptimal strategy called for these three fisheris to be operated at zero profit level involving a total fishing effort of more than 20 million hours fishing.

Of the remaining four fisheries, three should be operated at some economically profitable levels. These were associated with species 2, species 4 and species 5, each generating an annual profit of about £29 million, £99 million and £18 million from a respective harvest of about 31000, 674000 and 300000 metric tons while conserving the stocks at a steady level of about 967000, 7.31 million and 1.29 million metric tons by a combined fishing effort of about 19.6 million hours fishing (see table 6.15).

The last surviving species, species 10, on the other hand exhibited a suboptimal periodic harvest, a positive harvest for some years and a zero harvest

for other years. This 'chattering' type of harvesting occured after t = 10 years despite the relatively high stock level at about 3.0 million metric tons. The annual profit generated varied from zero (when the harvest was zero) to about £134 million (when t = 29, table 6.14).

The fishing mortality which is defined as the ratio between the harvest and the biomass for the non-depleting species (except species 10) varied from a relatively low 0.03 for species 2 to a relatively high 0.23 for species 5. The fishing mortality for species 10 varied from zero to a high 0.50 (at t = 29).

Due to the periodic harvesting of species 10, the total annual profit expected from the fishery fluctuated from about £150 million whenever the harvest of species 10 was zero to about £260 million. The maximum present value was estimated to be about £2880 million.

Comparison of the suboptimal harvest levels, h*(i) with the actual recorded harvests, h(i), i=1,...,10 (figures 6.3 to 6.12) for the first ten-year period suggested that the actual harvests were in general lower than the suggested suboptimal levels. Of the uneliminated species, only the actual harvest of species 10, h(10) appeared to be higher than the suboptimal harvest, h*(10). Of the three eliminated species, two of the actual harvest paths associated with species 7 and species 9, h(7) and h(9) appeared to suggest a possible low harvest in the future.

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	981500	123200	7649	33898.929
1.00	1650603	149132	5506	35550.042
2.00	1951118	190595	5953	30585.945
3.00	7141575	279142	2382	-15.642
4.00	6301240	278820	2696	-15.606
5.00	5375994	278349	3155	-15.553
6.00	4781374	277950	3542	-15.509
7.00	4366979	277608	3874	-15.470
8.00	4061651	277311	4161	-15.437
9.00	3827348	277052	4411	-15.409
10.00	3641888	276822	4632	-15.383
11.00	3491457	276618	4828	-15.360
12.00	3367005	276436	5003	-15.340
13.00	3262353	276271	5161	-15.322
14.00	3173141	276123	5303	-15.305
15.00	3096200	275988	5432	-15.290
16.00	3029175	275865	5550	-15.277
17.00	2970276	275752	5657	-15.264
18.00	2918122	275648	5756	-15.253
19.00	2871625	275553	5847	-15.242
20.00	2829923	275464	5932	-15.232
21.00	2792317	275382	6010	-15.223
22.00	2758241	275306	6082	-15.215
23.00	2727227	275235	6150	-15.207
24.00	2698887	275168	6213	-15.200
25.00	2672894	275106	6272	-15.193
26.00	2648975	275048	6327	-15.186
27.00	2626896	274993	6379	-15.180
28.00	2606457	274942	6428	-15.175
29.00	2587487	274893	6474	-15.169
30.00	2569837	274848	6517	-15.164

Table 6.5 Suboptimal time paths for species 1:Plaice
(Fishing Effort in '000 HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	52700	21100	13902	23009.894
1.00	58201	29379	17528	25308.979
2.00	453214	34541	2646	28474.222
3.00	2624520	31565	418	29214.643
4.00	990182	31483	1104	29063.400
5.00	768368	31445	1421	28993.419
6.00	769475	31445	1419	28993.868
7.00	816760	31455	1337	29011.920
8.00	891951	31469	1225	29036.692
9.00	953680	31478	1146	29054.116
10.00	973735	31481	1123	29059.303
11.00	976362	31481	1120	29059.966
12.00	976066	31481	1120	29059.892
13.00	975968	31481	1120	29059.867
14.00	975981	31481	1120	29059.870
15.00	975870	31481	1120	29059.842
16.00	976022	31481	1120	29059.881
17.00	975871	31481	1120	29059.843
18.00	976029	31481	1120	29059.882
19.00	975910	31481	1120	29059.852
20.00	975936	31481	1120	29059.859
21.00	976015	31481	1120	29059.879
22.00	975834	31481	1120	29059.833
23.00	976075	31481	1120	29059.894
24.00	975837	31481	1120	29059.834
25.00	976015	31481	1120	29059.879
26.00	975967	31481	1120	29059.867
27.00	975882	31481	1120	29059.845
28.00	976070	31481	1120	29059.893
29.00	975789	31481	1120	29059.822
30.00	976063	31481	1120	29059.891

Table 6.6 Suboptimal time paths for species 2: C.Sole

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	1052000	346300	7700	43575.381
1.00	3154823	364351	2702	51565.022
2.00	5088147	407243	1872	40257.186
3.00	6751893	490683	1700	2507.006
4.00	7724531	496001	1502	16.275
5.00	8191026	496369	1418	16.288
6.00	8389506	496513	1384	16.293
7.00	8469605	496569	1371	16.295
8.00	8501237	496591	1366	16.296
9.00	8513622	496600	1364	16.296
10.00	8518455	496603	1364	16.296
11.00	8520338	496604	1363	16.296
12.00	8521071	496605	1363	16.296
13.00	8521357	496605	1363	16.296
14.00	8521468	496605	1363	16.296
15.00	8521511	496605	1363	16.296
16.00	8521528	496605	1363	16.296
17.00	8521535	496605	1363	16.296
18.00	8521537	496605	1363	16.296
19.00	8521538	496605	1363	16.296
20.00	8521539	496605	1363	16.296
21.00	8521539	496605	1363	16.296
22.00	8521539	496605	1363	16.296
23.00	8521539	496605	1363	16.296
24.00	8521539	496605	1363	16.296
25.00	8521539	496605	1363	16.296
26.00	8521539	496605	1363	16.296
27.00	8521539	496605	1363	16.296
28.00	8521539	496605	1363	16.296
29.00	8521539	496605	1363	16.296
30.00	8521539	496605	1363	16.296

Table 6.7 Suboptimal time paths for species 3: Cod

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	1008400	231200	6399	46577.792
1.00	2533856	644667	7101	90793.421
2.00	2200872	648736	8227	88860.272
3.00	1441317	610571	11824	81443.411
4.00	8256125	675843	2285	99787.197
5.00	6465821	672021	2901	98661.652
6.00	6296610	671547	2977	98522.609
7.00	6466767	672023	2901	98662.409
8.00	6796699	672879	2763	98913.783
9.00	7145780	673698	2631	99154.773
10.00	7286759	674007	2582	99245.629
11.00	7310454	674057	2574	99260.560
12.00	7311519	674060	2573	99261.229
13.00	7308674	674053	2574	99259.441
14.00	7310970	674058	2573	99260.884
15.00	7308590	674053	2574	99259.389
16.00	7310029	674056	2574	99260.293
17.00	7309819	674056	2574	99260.161
18.00	7309294	674055	2574	99259.831
19.00	7310651	674058	2573	99260.683
20.00	7308644	674053	2574	99259.423
21.00	7310534	674057	2574	99260.610
22.00	7308743	674054	2574	99259.485
23.00	7310182	674057	2574	99260.389
24.00	7309880	674056	2574	99260.200
25.00	7309347	674055	2574	99259.865
26.00	7310501	674057	2574	99260.589
27.00	7308562	674053	2574	99259.371
28.00	7310793	674058	2573	99260.773
29.00	7308776	674054	2574	99259.505
30.00	7310217	674057	2574	99260.411

Table 6.8 Suboptimal time paths for species 4: Haddock

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	615300	198600	20197	19250.770
1.00	2333901	275305	7381	24475.935
2.00	3992148	515856	8086	-2.722
3.00	99086	31726	20035	313.038
4.00	23124	0.00	0.00	0.000
5.00	94678	24505	16195	104.270
6.00	242210	167620	43304	10754.809
7.00	560404	260104	29043	18350.463
8.00	1005436	288688	17967	21273.187
9.00	1252701	285736	14273	22378.591
10.00	1296635	298159	14389	22077.421
11.00	1295968	286838	13850	22480.178
12.00	1293895	296478	14338	22135.080
13.00	1293923	288832	13968	22409.708
14.00	1293522	292334	14142	22288.275
15.00	1293762	295380	14286	22176.852
16.00	1293752	288141	13936	22431.783
17.00	1293562	299382	14482	22018.023
18.00	1293875	286957	13878	22470.046
19.00	1293490	295816	14310	22159.357
20.00	1293838	289493	14001	22387.467
21.00	1293663	291032	14077	22334.483
22.00	1293681	297017	14366	22113.369
23.00	1293791	287596	13910	22449.461
24.00	1293522	298813	14455	22041.155
25.00	1293828	287042	13882	22467.198
26.00	1293608	294689	14255	22202.415
27.00	1293774	290333	14042	22358.859
28.00	1293685	290176	14036	22363.930
29.00	1293635	301405	14579	21933.648
30.00	1293750	287237	13893	22460.797

Table 6.9 Suboptimal time paths for species 5: Saithe

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	197400	108800	12610	4222.089
1.00	1836	0.000	0.000	0.000
2.00	0.000	0.000	0.000	0.000
3.00	0.000	0.000	0.000	0.000
4.00	0.000	0.000	0.000	0.000
5.00	0.000	0.000	0.000	0.000
6.00	0.000	0.000	0.000	0.000
7.00	0.000	0.000	0.000	0.000
8.00	0.000	0.000	0.000	0.000
9.00	0.000	0.000	0.000	0.000
10.00	0.000	0.000	0.000	0.000
11.00	0.000	0.000	0.000	0.000
12.00	0.000	0.000	0.000	0.000
13.00	0.000	0.000	0.000	0.000
14.00	0.000	0.000	0.000	0.000
15.00	0.000	0.000	0.000	0.000
16.00	0.000	0.000	0.000	0.000
17.00	0.000	0.000	0.000	0.000
18.00	0.000	0.000	0.000	0.000
19.00	0.000	0.000	0.000	0.000
20.00	0.000	0.000	0.000	0.000
21.00	0.000	0.000	0.000	0.000
22.00	0.000	0.000	0.000	0.000
23.00	0.000	0.000	0.000	0.000
24.00	0.000	0.000	0.000	0.000
25.00	0.000	0.000	0.000	0.000
26.00	0.000	0.000	0.000	0.000
27.00	0.000	0.000	0.000	0.000
28.00	0.000	0.000	0.000	0.000
29.00	0.000	0.000	0.000	0.000
30.00	0.000	0.000	0.000	0.000

Table 6.10 Suboptimal time paths for species 6: Whiting

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	634000	608300	92389	26470.879
1.00	159656	150702	90892	5961.369
2.00	5447994	484165	8557	49982.804
3.00	4778175	470142	9474	49742.293
4.00	43	0.000	0.000	0.000
5.00	0.000	0.000	0.000	0.000
6.00	0.000	0.000	0.000	0.000
7.00	0.000	0.000	0.000	0.000
8.00	0.000	0.000	0.000	0.000
9.00	0.000	0.000	0.000	0.000
10.00	0.000	0.000	0.000	0.000
11.00	0.000	0.000	0.000	0.000
12.00	0.000	0.000	0.000	0.000
13.00	0.000	0.000	0.000	0.000
14.00	0.000	0.000	0.000	0.000
15.00	0.000	0.000	0.000	0.000
16.00	0.000	0.000	0.000	0.000
17.00	0.000	0.000	0.000	0.000
18.00	0.000	0.000	0.000	0.000
19.00	0.000	0.000	0.000	0.000
20.00	0.000	0.000	0.000	0.000
21.00	0.000	0.000	0.000	0.000
22.00	0.000	0.000	0.000	0.000
23.00	0.000	0.000	0.000	0.000
24.00	0.000	0.000	0.000	0.000
25.00	0.000	0.000	0.000	0.000
26.00	0.000	0.000	0.000	0.000
27.00	0.000	0.000	0.000	0.000
28.00	0.000	0.000	0.000	0.000
29.00	0.000	0.000	0.000	0.000
30.00	0.000	0.000	0.000	0.000

Table 6.11 Suboptimal time paths for species 7: Herring

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	1268300	92400	12456	3358.420
1.00	7900594	1753552	37947	11946.642
2.00	31655397	2124362	11474	-5.433
3.00	33951749	2124825	10700	-5.436
4.00	25000715	2122538	14515	-5.424
5.00	20899509	2120835	17350	-5.415
6.00	22206056	2121446	16333	-5.418
7.00	23851749	2122120	15211	-5.422
8.00	25749300	2122790	14095	-5.425
9.00	26445835	2123012	13725	-5.426
10.00	26725960	2123098	13582	-5.427
11.00	26782717	2123115	13553	-5.427
12.00	26744048	2123104	13573	-5.427
13.00	26824445	2123128	13532	-5.427
14.00	26723167	2123097	13583	-5.427
15.00	26827272	2123129	13531	-5.427
16.00	26755219	2123107	13567	-5.427
17.00	26775478	2123113	13557	-5.427
18.00	26792160	2123118	13548	-5.427
19.00	26734709	2123101	13577	-5.427
20.00	26823700	2123128	13532	-5.427
21.00	26736944	2123101	13576	-5.427
22.00	26818263	2123126	13535	-5.427
23.00	26758149	2123108	13565	-5.427
24.00	26764398	2123110	13562	-5.427
25.00	26794322	2123119	13547	-5.427
26.00	26740042	2123102	13575	-5.427
27.00	26822950	2123127	13533	-5.427
28.00	26735633	2123101	13577	-5.427
29.00	26808034	2123123	13540	-5.427
30.00	26759517	2123108	13565	-5.427

Table 6.12 Suboptimal time paths for species 8: Sprat

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	1004700	182200	205761	4339.330
1.00	46879	0.000	0.000	0.000
2.00	0.000	0.000	0.000	0.000
3.00	0.000	0.000	0.000	0.000
4.00	0.000	0.000	0.000	0.000
5.00	0.000	0.000	0.000	0.000
6.00	0.000	0.000	0.000	0.000
7.00	0.000	0.000	0.000	0.000
8.00	0.000	0.000	0.000	0.000
9.00	0.000	0.000	0.000	0.000
10.00	0.000	0.000	0.000	0.000
11.00	0.000	0.000	0.000	0.000
12.00	0.000	0.000	0.000	0.000
13.00	0.000	0.000	0.000	0.000
14.00	0.000	0.000	0.000	0.000
15.00	0.000	0.000	0.000	0.000
16.00	0.000	0.000	0.000	0.000
17.00	0.000	0.000	0.000	0.000
18.00	0.000	0.000	0.000	0.000
19.00	0.000	0.000	0.000	0.000
20.00	0.000	0.000	0.000	0.000
21.00	0.000	0.000	0.000	0.000
22.00	0.000	0.000	0.000	0.000
23.00	0.000	0.000	0.000	0.000
24.00	0.000	0.000	0.000	0.000
25.00	0.000	0.000	0.000	0.000
26.00	0.000	0.000	0.000	0.000
27.00	0.000	0.000	0.000	0.000
28.00	0.000	0.000	0.000	0.000
29.00	0.000	0.000	0.000	0.000
30.00	0.000	0.000	0.000	0.000

Table 6.13 Suboptimal time paths for species 9: Mackerel

(Fishing Effort in '000HF)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
0.00	2407100	1019900	17034	111824.379
1.00	3239598	1536445	19067	136442.131
2.00	5598069	1631480	11716	153843.136
3.00	2098915	0.00	0.00	0.000
4.00	1949809	0.00	0.00	0.000
5.00	2203342	0.00	0.00	0.000
6.00	2554354	0.00	0.00	0.000
7.00	2794714	0.00	0.00	0.000
8.00	2982031	1113158	15007	123580.923
9.00	2957672	549159	7465	78741.273
10.00	3028746	0.00	0.00	0.000
11.00	2956674	535673	7284	77220.063
12.00	3010066	0.00	0.00	0.000
13.00	2973396	898571	12149	110829.364
14.00	2982366	0.00	0.00	0.000
15.00	3013798	1303185	17384	130752.421
16.00	2960504	261842	3556	41899.949
17.00	3031638	0.00	0.00	0.000
18.00	2957790	593345	8065	83562.223
19.00	3005124	0.00	0.00	0.000
20.00	2977446	963056	13004	115230.509
21.00	2976026	11260	152	1966.613
22.00	3022642	1374850	18286	132360.380
23.00	2957433	314665	4277	49382.636
24.00	3026949	0.00	0.00	0.000
25.00	2958617	652280	8863	89645.304
26.00	2998819	0.00	0.00	0.000
27.00	2982588	1028700	13866	119231.933
28.00	2970533	59766	809	10267.581
29.00	3047781	1522248	20080	133932.294
30.00	2955408	368576	5014	56687.583

Table 6.14 Suboptimal time paths for species 10: Others

(Fishing Effort in '000HF)

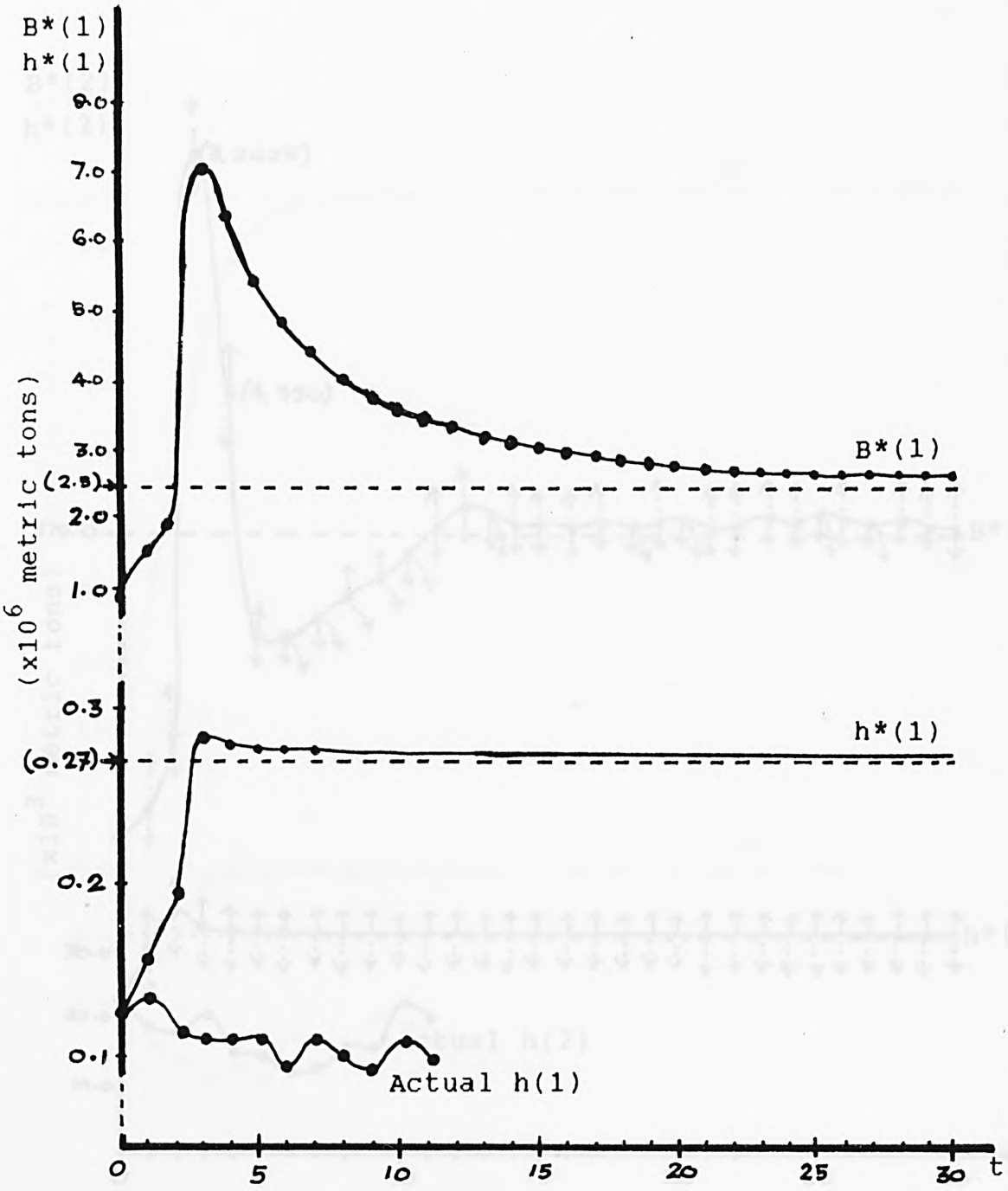


Figure 6.3 Suboptimal time paths for species 1: Plaice (fishing effort in '000HF)

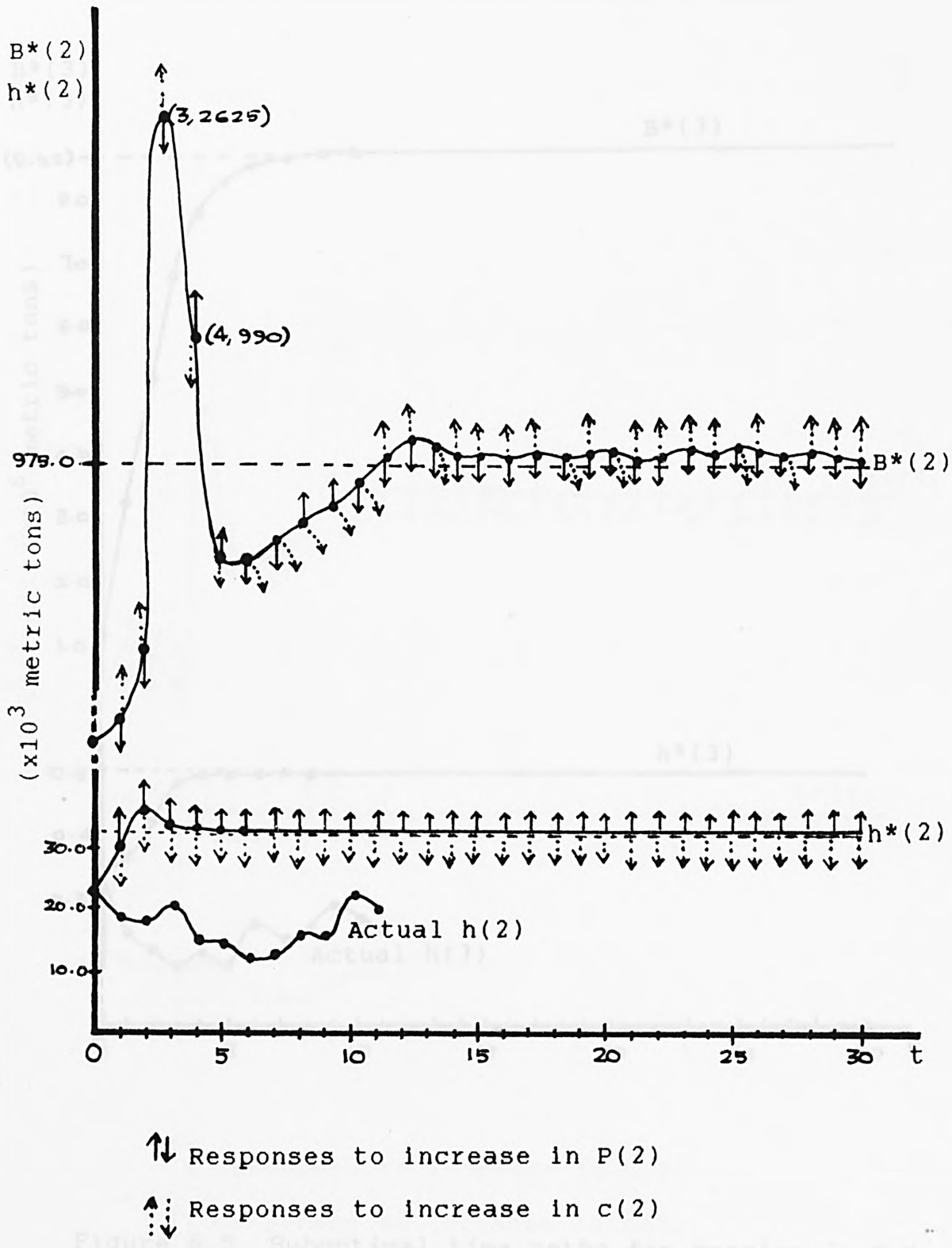


Figure 6.4 Suboptimal time paths for species 2: C.Sole (fishing effort in '000HF)

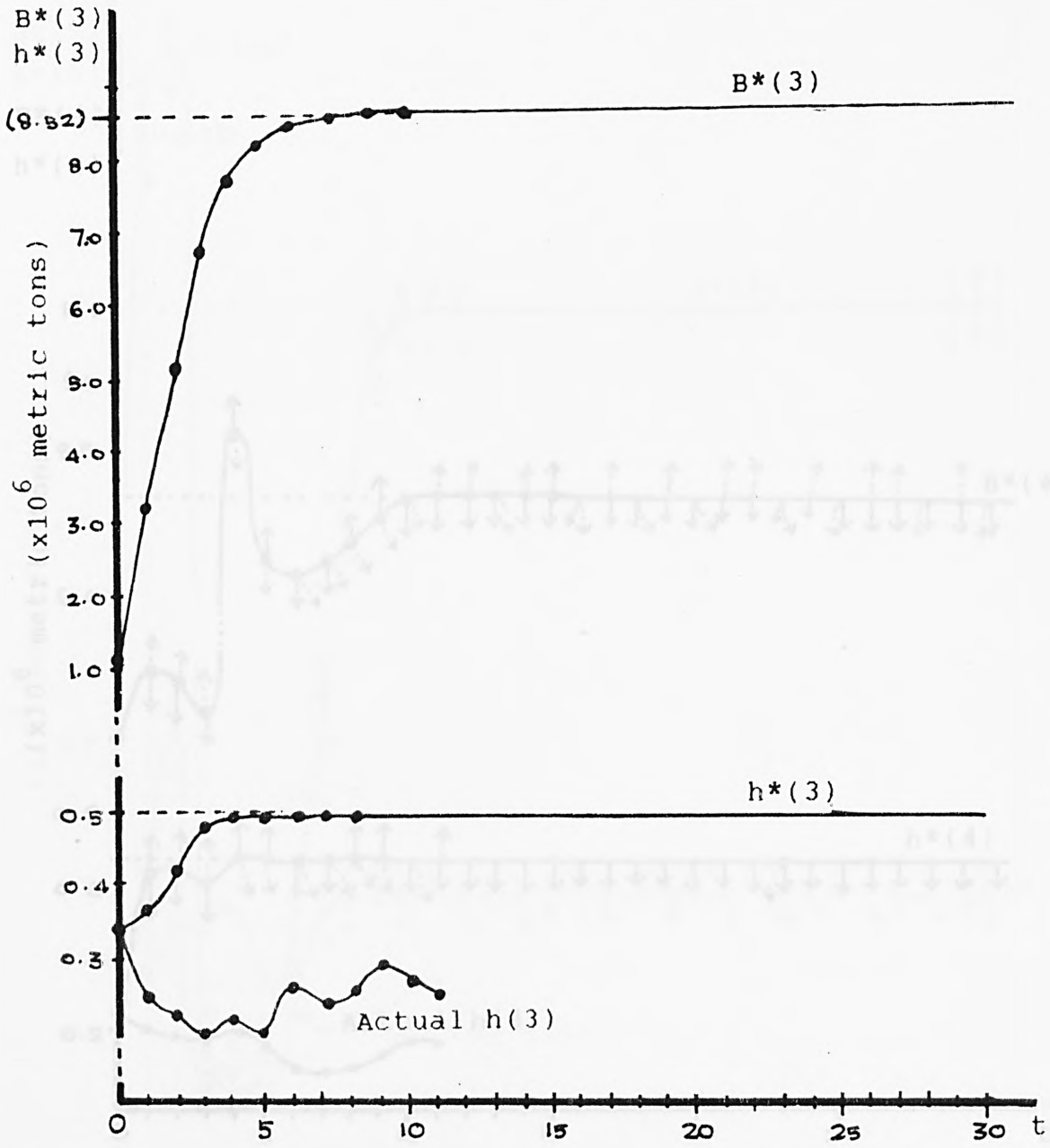


Figure 6.5 Suboptimal time paths for species 3: Cod (fishing effort in '000HF)

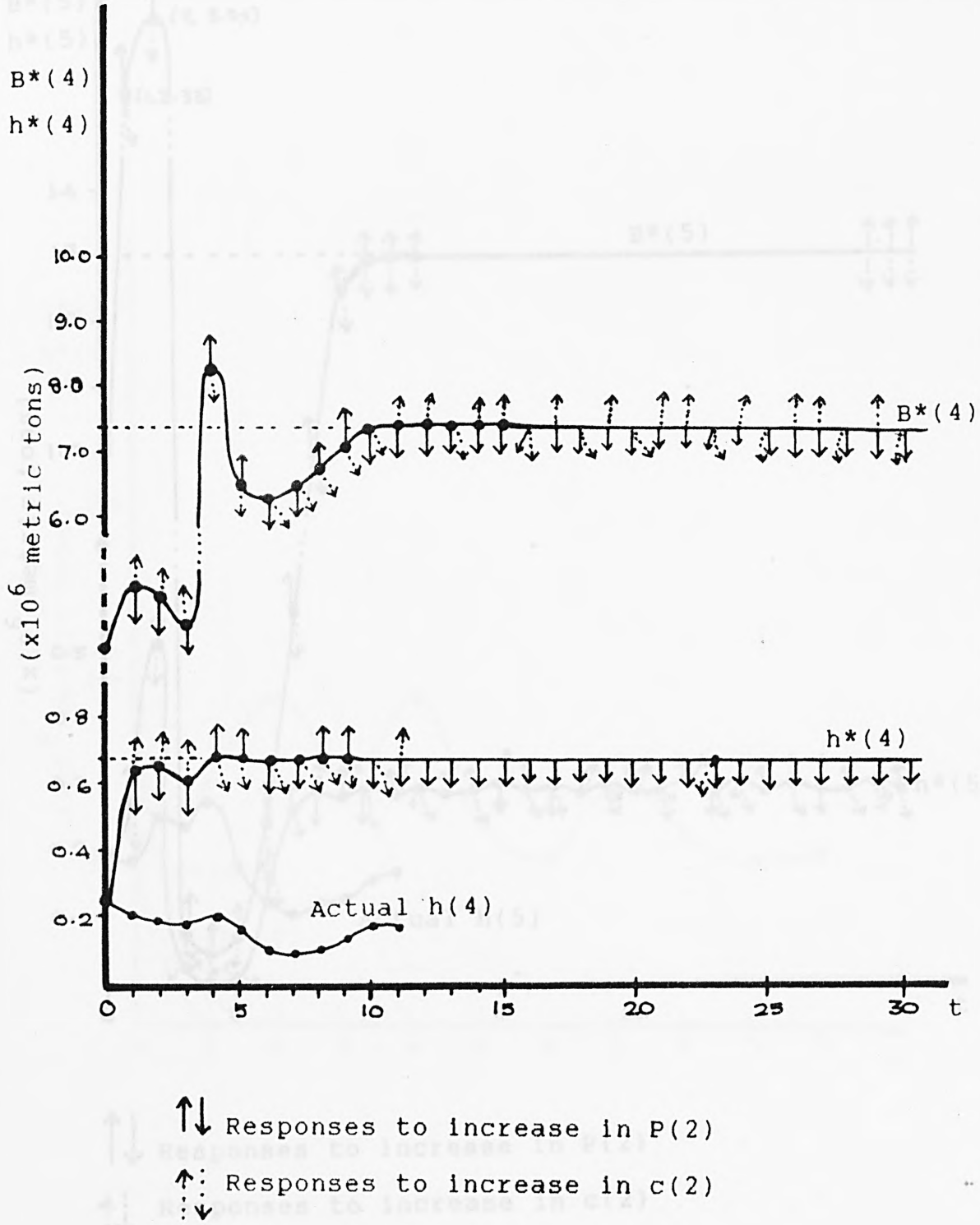


Figure 6.6 Suboptimal time paths for species 4: Haddock (fishing effort in '000HF)

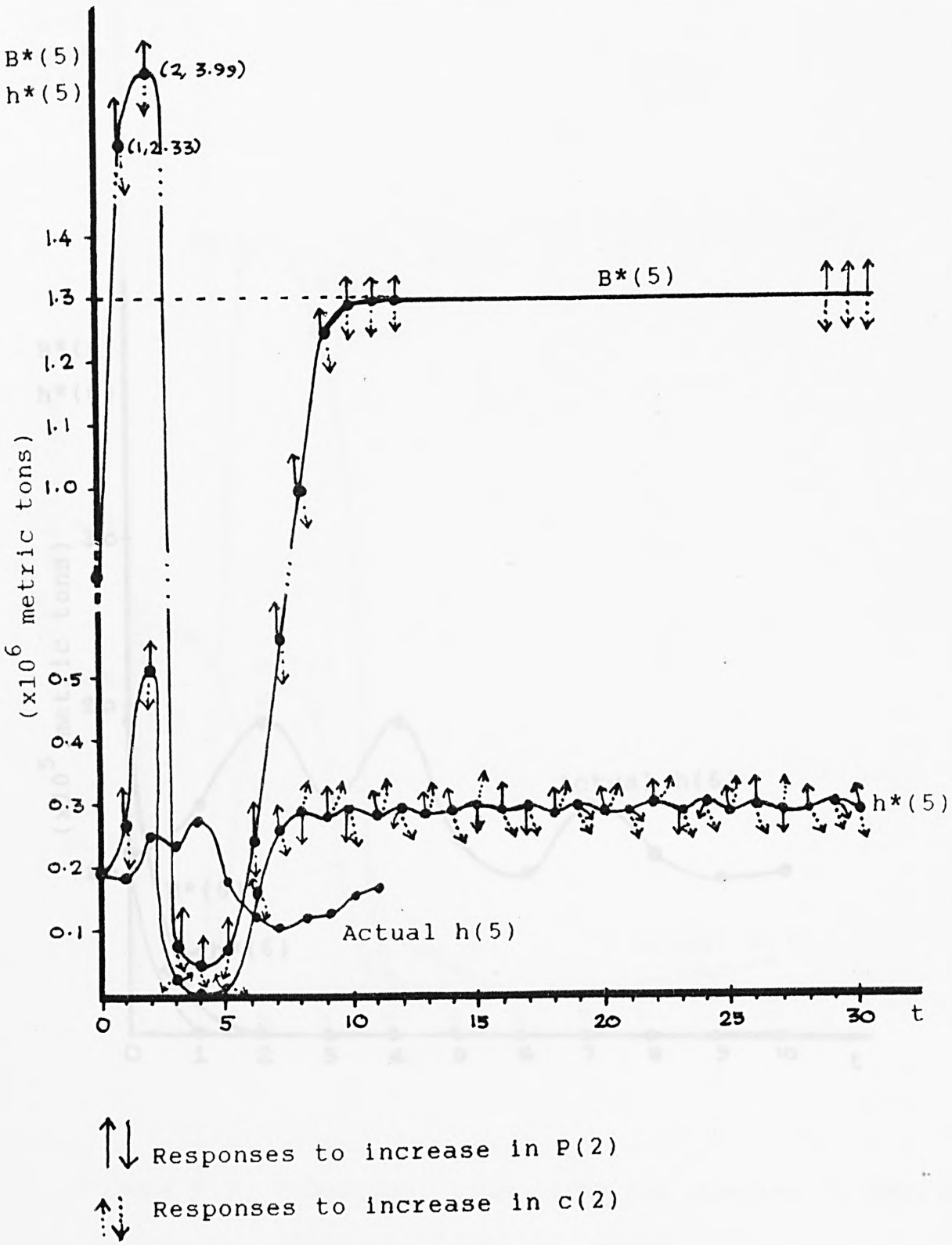


Figure 6.7 Suboptimal time paths for species 5: Saithe (fishing effort in '000HF)

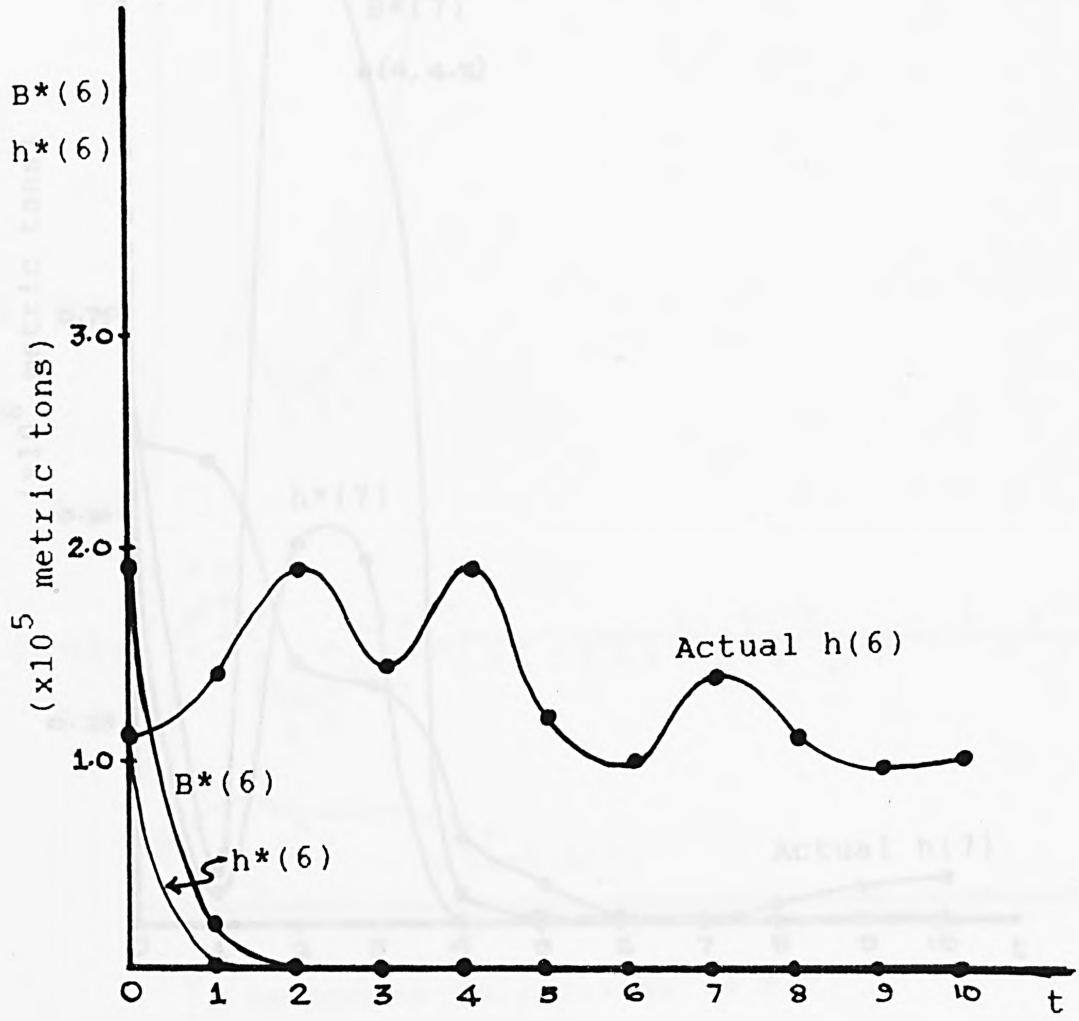


Figure 6.8 Suboptimal time paths for species 6: Whiting (fishing effort in '000HF)

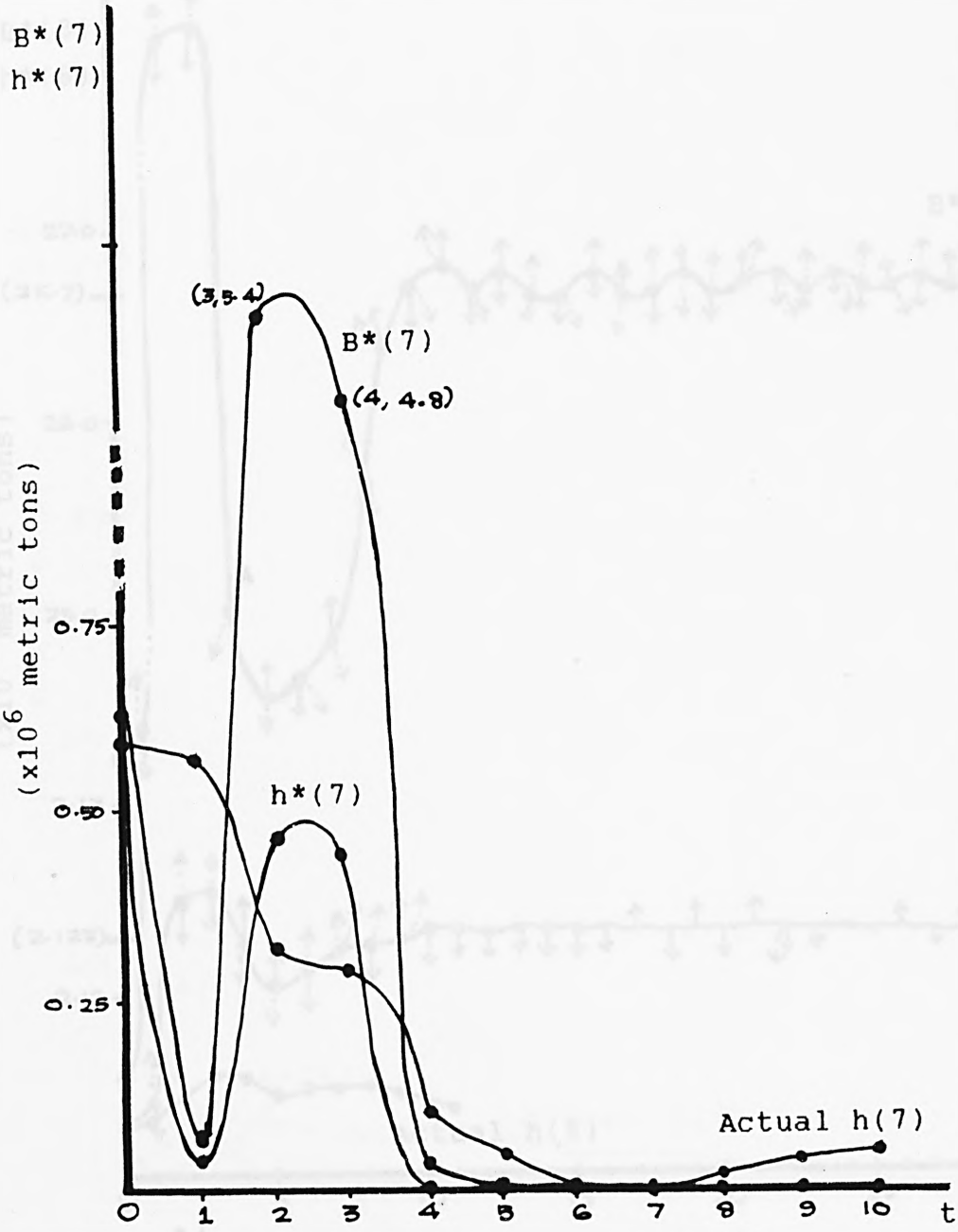


Figure 6.9 Suboptimal time paths for species 7: Herring (fishing effort in '000HF)

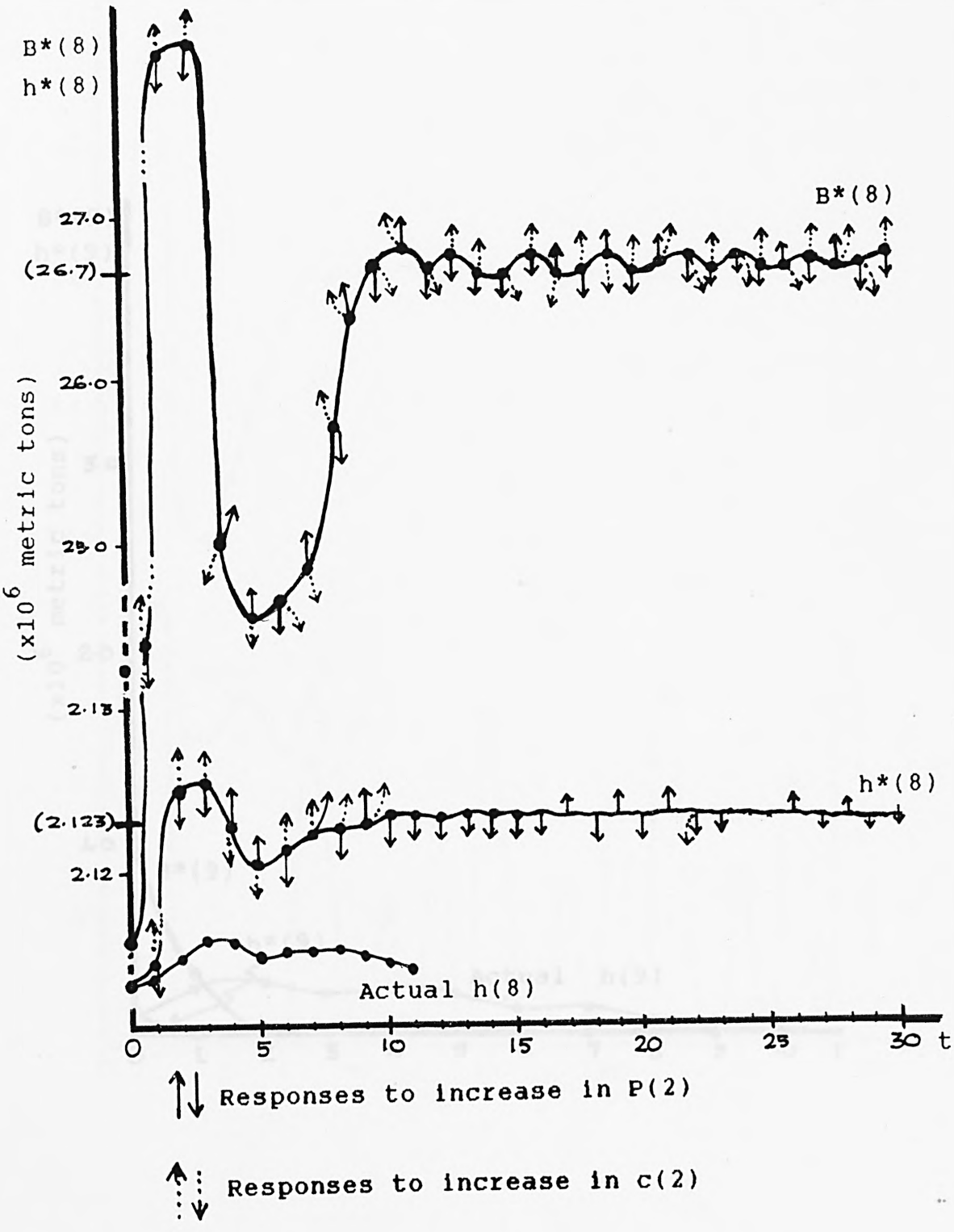


Figure 6.10 Suboptimal time paths for species 8: Sprat

(fishing effort in '000HF)

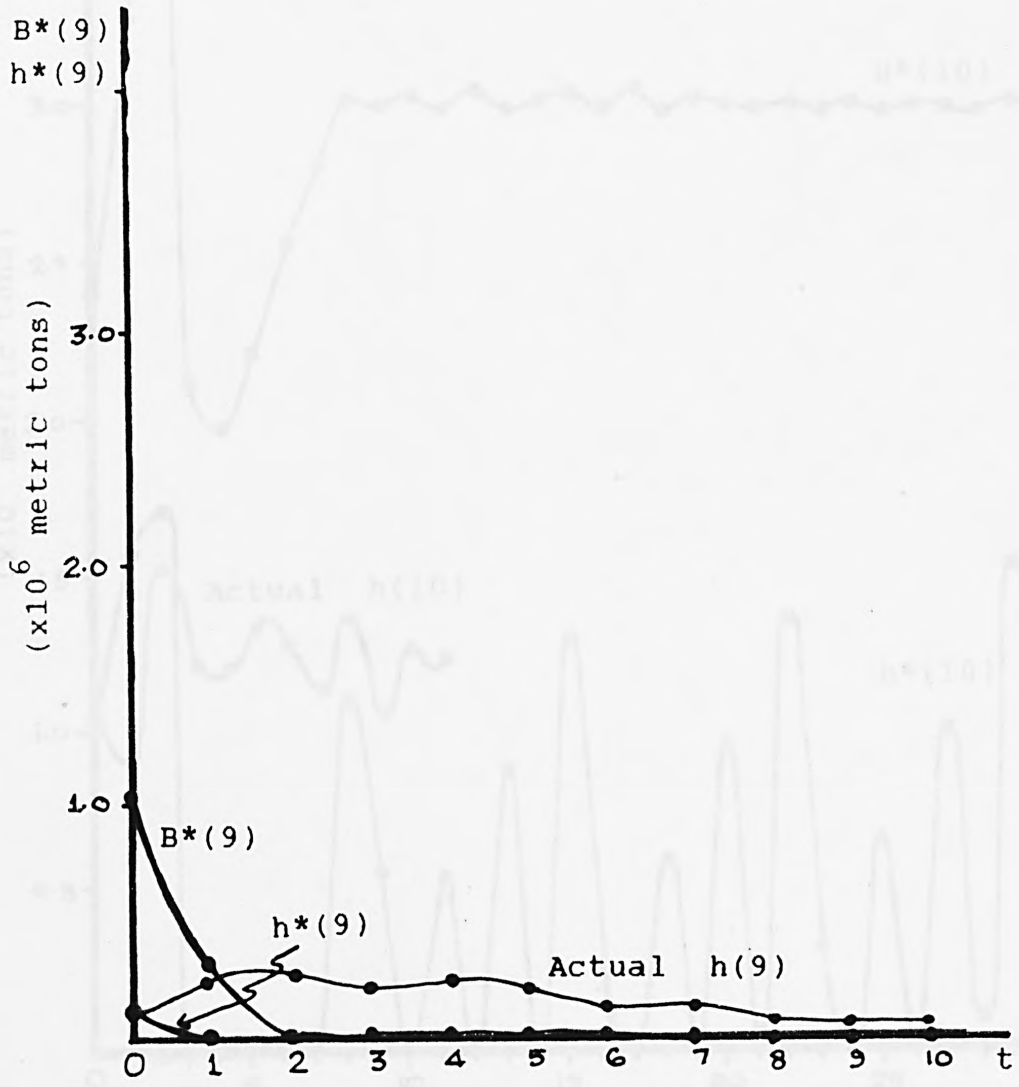


Figure 6.11 Suboptimal time paths for species 9: Mackerel (fishing effort in '000HF)

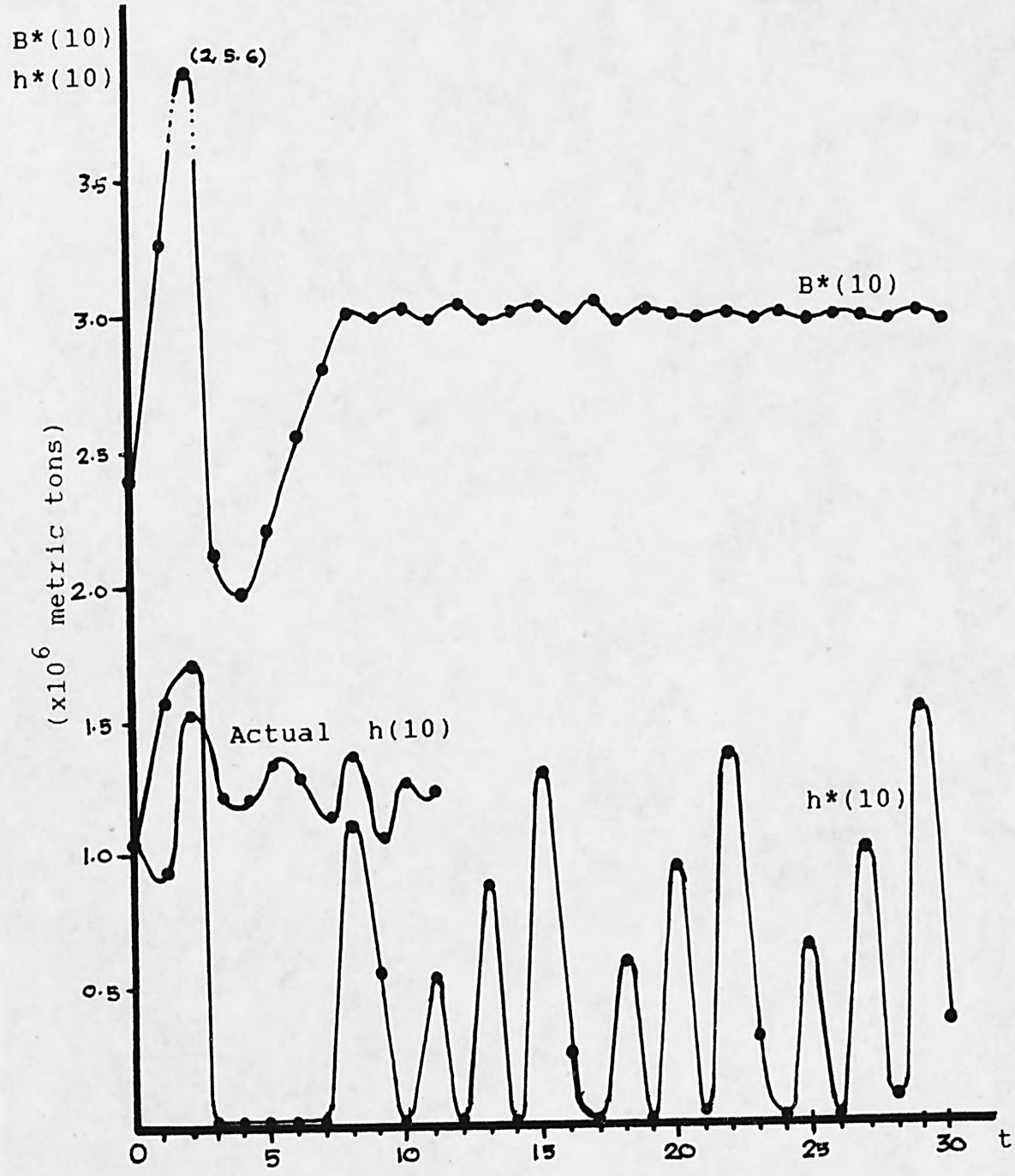


Figure 6.12 Suboptimal time paths for species 10: Others (fishing effort in '000HF)

SPECIES(i)	BIOMASS (metric tons)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
1.PLAICE	2569840	274848	6517	-15.164
2.C.SOLE	976063	31481	1120	29059.900
3. COD	8521540	496605	1363	16.296
4.HADDOCK	7310220	674057	2574	99260.400
5.SAITHE	1293750	287237	13893	22460.800
6.WHITING	...	...	...	...
7.HERRING	...	...	...	...
8.SPRAT	26759500	2123110	13565	-5.427
9.MACKEREL	...	...	...	...
10.OTHERS	2955410	368576	5014	56687.600

TOTAL ECONOMIC PROFIT : £207.464 MILLION

PRESENT VALUE : £2878.867 MILLION

Table 6.15 Long run (t=30) suboptimal level when discount rate is 7.5%

(Fishing Effort in '000HF)

6.5.2 Sensitivity Tests

6.5.2.1 Increase in discount rate

The discount rate was increased from 7.5% to 15.0% and finally to 30.0%. In the first few years, the harvest of each species increased, thus decreasing their biomasses. However, as the biomasses decreased further, the harvests in the long run decreased as well despite increases in the fishing efforts. Thus it appeared that the level of harvest is dictated by the level of biomass rather than the fishing effort.

Table 6.16 summarises the long run suboptimal levels (when t = 30) when the discount rate was increased to 15.0% and 30.0%. The present value decreased to £1544 million and £874 million respectively while the total annual economic profit generated for both cases remained at about £150 million, subject to the annual fluctuations in the profit generated by the harvesting of species 10.

6.5.2.2 Increase in unit price

For simplicity we will consider increases in the unit price of species 2 (for predator-prey and symbiotic cases) and species 4 (for the competitive case).

The price demand curve of species 2 was shifted by 30% from

$$P(2,t) = 1853.9 - 2.9319(10^{-2})h(2,t) \quad (6.24)$$

to

$$P(2,t) = 2410.1 - 2.9319(10^{-2})h(2,t). \quad (6.25)$$

SPECIES (i)	BIOMASS (metric tons)	HARVEST	F.EFFORT ('000HF)	PROFIT (£'000)
1.PLAICE	2569860 (2569920)	274848 (274848)	6517 (6517)	-15.164 (-15.164)
2.C.SOLE	975859 (975710)	31481 (31481)	1120 (1120)	29059.800 (29059.800)
3. COD	8521540 (8521540)	496605 (496605)	1363 (1363)	16.296 (16.296)
4.HADDOCK	7319210 (7309170)	674057 (674055)	2574 (2574)	99260.400 (99259.800)
5.SAITHE	1292840 (1291020)	294924 (290300)	14275 (14507)	22191.200 (22013.300)
6.WHITING	...	...	...	...
7.HERRING	...	...	...	...
8.SPRAT	26729300 (26752100)	2123100 (2123110)	13580 (13569)	-5.427 (-5.427)
9.MACKEREL	...	...	...	...
10.OTHERS	2993260 (3008840)	0.00 (0.00)	0.00 (0.00)	0.000 (0.000)

TOTAL ECONOMIC PROFIT : £150.507 MILLION
(£150.329 MILLION)

PRESENT VALUE : £1544.393 MILLION
(£874.292 MILLION)

Note: Figures in brackets refer to case where the discount rate was increased to 30.0%

Table 6.16 Long run (t=30) suboptimal level when the discount rate is 15.0% (30.0%). (Fishing Effort in '000HF).

In response to this shift in price, the harvest of species 2 increased for all t > 1.0, and so did the fishing effort. This resulted in a decrease in the stock level except at t = 4, 5, 8 and 9. At times t = 4 and 5, the stocks were decreasing. A complete picture of these responses by the biomass and harvest are illustrated in figure 6.4. The long run equilibrium (at t = 30) was established at a lower biomass level of about 972700 metric tons, a higher harvest level of about 41000 metric tons and a higher fishing effort level of about 1.462 million hours fishing.

Species 2 is a prey to species 4 (or in other words, species 4 is a predator to species 2). Thus changes in the stock of species 2 would induce similar changes in the stock of species 4. Following a decrease in the biomass of species 2, the biomass of species 4 also decreased except at t = 4, 5, 8 and 9. Changes in the harvest of species 4 closely followed the changes in its biomass — a decrease except at t = 4,5,8 and 9. The fishing effort increased except at times when the biomass increased. A complete picture of these responses by the biomass and the harvest are depicted in figure 6.6. The long run equilibrium (at t = 30) was established at a lower biomass level of about 7.293 million metric tons, a slightly lower harvest level of about 674000 metric tons and a slightly higher fishing effort level of about 2.580 million hours fishing.

In addition to being a prey to species 4, species 2 also preys on species 5. Thus we would expect species 5 to exhibit responses opposite to those exhibited by species 4. The biomass of species 5 increased for all $t > 1.0$ due to the decrease in the predator stock of species 2. It seemed that the increase in the stock of species 2 at consecutive times $t = 4$ and 5, and $t = 8$ and 9 had no inhibiting effect on the growth of species 5. The harvest, however showed a general increase only in the early periods but fluctuated slightly for $t > 8.0$. This could be largely due to the slightly fluctuating nature of its original control (harvest) solution. The fishing effort on the other hand decreased in the early periods and fluctuated slightly in the later periods. Figure 6.7 gives a complete picture of these responses by the biomass and harvest. A long run ($t = 30$) equilibrium was established at a higher biomass level of about 1.310 million metric tons, a slightly higher harvest and fishing effort levels of about 298000 metric tons and 14.270 million hours fishing respectively.

The results in Chapter 5 suggested a symbiotic type of species interaction between species 2 and species 8. We should then expect the biomass of species 8 to follow a similar pattern of response as that exhibited by the biomass of species 2. But this did not seem to be the case.

SPECIES	t=5.0	t=10.0	t=20.0	t=30.0
SPE.2				
B(2)	773301	971926	972781	972737
h(2)	40931	40966	40966	40966
E(2)	1838	1464	1462	1462
PREDATOR				
B(4)	6517080	7279920	7294440	7293000
h(4)	672159	673992	674023	674020
E(4)	2879	2584	2579	2580
PREY				
B(5)	106306	1314210	1308760	1308930
h(5)	53244	288369	296342	298545
E(5)	31340	13730	14169	14272
SYM.CASE				
B(8)	21126500	26703100	26727600	26792100
h(8)	2120950	2123090	2123100	2123120
E(8)	17164	13593	13581	13548

Table 6.17 Sensitivity tests for increase in unit price of species 2.
(Fishing Effort in '000HF)

Despite the general decrease in the biomass of species 2, changes in the level of the biomass of species 8 seemed to fluctuate (decrease and increase) every few years. Its harvest also responded similarly, decreased whenever the biomass decreased and increased whenever the biomass increased. The fishing effort on the other hand responded in the opposite direction. Thus it appeared that when the biomass is at a high level (in the case of species 8, the biomass was about 27 million metric tons) and with the fishery operating at the bioeconomic equilibrium level, changes in the biomass of a symbiotic partner tend to have minimum effect on the biomass of that species. A complete picture of the responses by the biomass and harvest of species 8 are depicted in figure 6.10. The long run equilibrium (at t = 30) was established with the biomass at a slightly higher level of about 26.792 million metric tons, an approximately identical harvest level of about 2.123 million metric tons and a slightly lower level of fishing effort of about 13.55 million hours fishing.

The only remaining pair of competitiuve species in the simulation were species 4 and species 10. In order to investigate their sensitivities, the price (demand) curve of species 4 was shifted by 30% from

$$P(4,t) = 301.38 - 2.1854(10^{-4})h(4,t) \quad (6.26)$$

to

$$P(4,t) = 391.80 - 2.1854(10^{-4})h(4,t). \quad (6.27)$$

As with species 2, the harvest of species 4 increased for all $t \neq 3.0$, resulting in a decrease in its biomass (except at $t = 4$) and induced an increase in the fishing effort for all $t \neq 3.0$. The long run equilibrium (at $t = 30$) was established at a lower biomass level of about 7.285 million metric tons and a higher harvest and fishing effort levels of about 880911 metric tons and 3.375 million hours fishing respectively (see table 6.19).

Responses by its competitor, species 10 were not as conclusive as expected. The biomass generally increased slightly in the short run ($t < 4.0$) but no definite pattern was established in the long run. Since the suboptimality for this species involved a 'periodic' harvesting, no definite conclusion can be derived regarding the responses of its harvest and fishing effort. However, at $t = 30$, its biomass, harvest and fishing effort levels were relatively higher at about 2.965 million metric tons, 772390 metric tons and 10.472 million hours fishing respectively.

6.5.2.3 Increase in unit cost

The unit cost of composite fishing effort directed at species 2, c(2) was increased by 30.0% from £219.7 to £285.6 per thousand hours fishing.

In response to this increase, the harvest of species 2 decreased for all $t > 1.0$. Its biomass how-

ever increased in the first three years and decreased in the next six years. After that the biomass appeared to generally increase with a decrease once in about every five years. The fishing effort decreased during all periods except at t = 4 (when the biomass was decreasing). A complete picture of these responses by the biomass and the harvest are depicted in figure 6.4. A new long run (t = 30) equilibrium was established at a slightly higher level of biomass of about 976000 metric tons, a lower level of harvest and fishing effort of about 31440 metric tons and 1.118 million hours fishing respectively.

The biomass of the predator species, species 4 changed according to the changes of the biomass of its prey, species 2 — increased whenever the biomass of species 2 increased. Harvest of species 4 increased in the first three years, then decreased during the next six years (when the biomass of both species decreased), and remained approximately unchanged after t = 12.0. Fishing effort on the other hand showed a decrease whenever the biomass increased. These responses by the biomass and harvest of species 4 are shown in figure 6.6. Although the new long run equilibrium (t = 30) was established at a slightly lower biomass level of about 7310110 metric tons, the harvest remained unchanged at about 674057 metric tons. The level of fishing effort increased slightly to about 2.574 million hours fishing.

The biomass of the prey species, species 5, decreased for all t > 1.0, but not its harvest. The slightly perturbed nature of the suboptimal harvest curve caused an unpredictable response in the harvest level — increasing and decreasing every few years. A similar pattern of response was also exhibited by its fishing effort. The responses by the biomass and the harvest of species 5 to an increase in the unit cost of harvesting the predator species (species 2) are depicted in figure 6.7. The long run (t = 30) equilibrium was established at a lower biomass, harvest and fishing effort levels of about 1293700 metric tons, 287010 metric tons and 13.882 million hours fishing respectively.

As with the previously considered symbiotic case, changes in the biomass of species 2 as a result of an increase in its unit cost of harvesting appeared to have small long run effect on its symbiotioc partner, species 8. The biomass of species 8 fluctuated slightly during the years. The harvest, however, increased slightly in the first few years (except at t = 4 and 5), and finally settled at the previous maximum bioeconomic equilibrium level after t = 10.0. These responses are depicted in figure 6.10. The response by the fishing effort followed an opposite fluctuating pattern to that exhibited by the biomass. The long run equilibrium (t = 30) was established at a slightly higher biomass level of about 26765900 metric

tons, an unchanged harvest level of about 2123110 metric tons and a slightly lower fishing effort level of about 13.562 million hours fishing.

In order to investigate the sensitivities associated with the only remaining pair of competitive species, we increased the unit cost of the composite fishing effort directed at species 4 by 30% from £1784.50 to £2319.85 per thousand hours fishing.

Changes in species 4 followed a similar pattern as that exhibited by species 2 in response to increase in c(2). The harvest decreased for all $t > 1.0$ while the biomass increased in the first three years and decreased for the next two years. After $t = 12$, the biomass appeared to generally increase with a decrease once in every three or four years. The fishing effort on the other hand decreased for all $t \neq 4.0$. A new long run bioeconomic equilibrium ($t = 30$) was established at a higher biomass level of about 7.311 million metric tons, a lower harvest and fishing effort levels of about 669380 metric tons and 2.555 million hours fishing respectively. These responses at selected times are given in table 6.19.

As before, the responses by its competitor, species 10 remained less conclusive. The biomass, harvest and fishing effort fluctuated from year to year with a generally decreased levels in the long run (see table 6.19 for selected times). At $t = 30$, the biomass was at a relatively higher level of about 2.970 million

SPECIES	t=5.0	t=10.0	t=20.0	t=30.0
SPE.2				
B(2)	767712	973733	975930	976068
h(2)	31394	31441	31441	31441
E(2)	1420	1121	1119	1118
PREDATOR				
B(4)	6460980	7286520	7308620	7310110
h(4)	672007	674006	674053	674057
E(4)	2903	2582	2574	2574
PREY				
B(5)	94024	1296560	1293770	1293710
h(5)	21904	297699	290362	287014
E(5)	14577	14368	14044	13882
SYM.CASE				
B(8)	20881400	26725800	26827000	26765900
h(8)	2120830	2123100	2123130	2123110
E(8)	17365	13582	13531	13562

Table 6.18 Sensitivity tests for increase in unit cost of harvesting species 2.
(Fishing Effort in '000HF)

	t=5.0	t=10.0	t=20.0	t=30.0
Inc. in P(4)				
B(4)	6459150	7241030	7285250	7285250
h(4)	878911	880816	880911	880911
E(4)	3798	3395	3375	3375
B(10)	2197740	2980370	2965150	2965150
h(10)	0.00	974430	772389	772389
E(10)	0.00	13009	10472	10472
Inc. in c(4)				
B(4)	6460790	7289740	7310060	7311490
h(4)	666715	669322	669379	669383
E(4)	2880	2563	2556	2555
B(10)	2209540	3025100	2956850	2969690
h(10)	0.00	1375240	593470	600383
E(10)	0.00	18277	8069	813

Table 6.19 Sensitivity tests for competitive case
(Fishing Effort in '000HF)

metric tons but a relatively lower harvest of about 60038 metric tons. Its fishing effort also decreased to about 0.813 million hours fishing during the same period.

6.6 The Constrained Case:Fishing Effort in '000TH

6.6.1 The Suboptimal Time Paths

A similar computer simulation was performed for the model using thousand of ton-hours fishing as a measure of fishing effort with B(i,t) and h(i,t) assuming initial values given by equations (6.5) and (6.6) respectively. The parameters a(i,j), Q(i), c(i) and the function P(i,t) were as estimated in Chapter 5. As with previous case, the discount rate was assigned a value of 7.5%. The suboptimal paths obtained for each species are summarised in tables 6.20 to 6.29 and depicted in figures 6.13 to 6.22.

The suboptimal policy in this case also suggested variations in the strategy which included a complete elimination of some species, harvesting some species at their bioeconomic equilibrium levels as well as harvesting some species at some economically profitable levels. However, most of the suboptimal solutions exhibited significant perturbations in the long run, both in the biomass as well as the harvest levels.

Four of the species, namely species 2, species 5, species 7 and species 10 were finally eliminated. Species 7, however was not eliminated until

after 14 years while the other three species were simultaneously eliminated at an earlier time of two years.

Results in Chapter 5 indicated that these three species exhibited a mutually symbiotic type of species interaction between them. Thus it appeared that elimination of one or more partners in this case caused the elimination of all the remaining partners as well. In addition to this, these three species were also being preyed by as well as competing with other species. Despite being a predator to species 9, species 2 was also being preyed by species 4 and species 6 while at the same time competing with species 7 (which remained uneliminated in the early periods). Species 5, on the other hand, was not a predator and was being preyed upon by species 6 and species 7 while competing with species 9. While preying on species 3, species 10 was also being preyed by species 7 and species 9, and competing with species 6. This seemed to suggest that the predations and competitions by species 6, species 7 and species 9 on these three species outweighed their predations on other species, for example the predation of species 10 on species 3, and drove them out of the system.

The eliminations of species 5 and species 10 left species 7 with only one prey, species 1. This, together with the competition with the other remaining species led to its elimination at t=14. In the early

years before its elimination, its fishery was operating at the bioeconomic equilibrium level with dissipation of economic rent (a small profit of less than 4 pence per metric ton — table 6.26) while in the last two years of harvesting the fishery generated a total profit of more than £44 million.

One fishery, associated with species 4 should in the long run be closed and its stock left to decay slowly. Table 6.23 suggests that whenever the stock level was above 33000 metric tons, harvesting should commenced at the maximum bioeconomic level so as to drive the stock level as low as possible. The elimination of one of its preys, species 2 and the predation by species 6 also contributed to the decline of its stock. The abundance of its other prey, species 9 did not seem to have any positive effect. This seemed to suggest the elimination of the predator, species 4 while allowing the prey, species 9 to flourish.

Of the remaining five species, only species 1 should be harvested at some economically profitable level while the other four at their respective bioeconomic equilibrium levels. Although the stock and the harvest levels for species 1 in the long run were relatively low at about 110000 metric tons and 80000 metric tons respectively, the annual profit generated was more than £10 million and the fishing effort employed was more than 3400 million ton-hours fishing (table 6.20).

The four fisheries that were operating at the bioeconomic equilibrium levels were those associated with species 3, species 6, species 8 and species 9. Fishery associated with species 3 generated positive profits during two of its earlier years at t = 3 and 4 with a combined profit of more than £29 million (table 6.22). Although the fishery was operating at its bio-economic equilibrium level with an annual profit of less than 4 pence per metric ton in all other years, the levels of its biomass, harvest and fishing effort varied from year to year, fluctuating about the mean levels of 75000 metric tons, 60000 metric tons and 3500 million ton-hours fishing respectively.

Species 6, on the other hand appeared to be approaching a steady bioeconomic equilibrium with its biomass and harvest levels at about 2.2 million metric tons and 648000 metric tons respectively with an annual fishing effort of about 1636 million ton-hours fishing. A positive economic rent of about £8.93 million was generated at t = 11 (table 6.25) while in all other years the fishery was operating at a loss of less than 3 pence per metric ton of harvest per year (equivalent to the dissipation of economic rent).

The harvesting of species 8 did not commence until t = 16, when one of its competitors, species 7 had been completely eliminated. Although its biomass appeared to be approaching a steady equilibrium level of about 51300 metric tons, its harvest and fishing

effort exhibited some annual fluctuations. Their respective levels at t = 30 were about 35000 metric tons and 5980 million ton-hours fishing.

The suboptimal policy associated with species 9 suggested an approximately constant annual harvesting of about 1.10 million metric tons. However, despite being at a bioeconomic equilibrium level, the biomass fluctuated from a relatively low level of about 4.1 million metric tons to a relatively high level of about 6.6 million metric tons during the last ten years of the simulated period. As a result, its fishing effort also varied from a relatively low level of about 13250 million ton-hours fishing to a relatively high level of about 20250 million ton-hours fishing during the same period (table 6.28).

Since only the fishery associated with species 1 was operating at a profitable level, the total annual profit generated closely resembled that generated in this fishery. The total annual profit expected from the fishery from this optimal policy at t = 30 was about £13.043 million. The maximum present value was estimated to be about £535.186 million.

In contrast to the first case of fishing effort, suboptimality in this case suggested a very high fishing mortality. Except for species 6 and species 9 whose fishing mortalities were about 0.30 and 0.20 respectively, the fishing mortalities for the other non-depleting species were found to be above

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	610900	123200	972699	32865.753
1.00	1361009	135873	481516	36079.274
2.00	1103232	134727	589015	35473.229
3.00	590318	129470	1057840	32758.794
4.00	506672	127603	1214709	31820.904
5.00	468682	126535	1302180	31290.513
6.00	402743	124203	1487451	30147.862
7.00	330441	120577	1759977	28413.001
8.00	265385	115625	2101412	26127.100
9.00	200474	107480	2585882	22576.054
10.00	136445	91855	3247005	16488.988
11.00	89917	66540	3569238	8652.678
12.00	69505	44738	3104511	3911.419
13.00	67696	42170	3004592	3475.419
14.00	73352	49774	3272883	4841.699
15.00	82947	60302	3506423	7106.386
16.00	97943	72623	3576338	10307.118
17.00	120644	85447	3416100	14268.824
18.00	137963	92393	3230097	16682.825
19.00	122848	86440	3393790	14602.228
20.00	99241	73515	3572885	10561.809
21.00	92164	68350	3576940	9129.842
22.00	97741	72482	3576778	10267.250
23.00	109829	79999	3513217	12507.108
24.00	120834	85534	3414203	14297.879
25.00	119646	84986	3425988	14115.117
26.00	108029	78986	3526539	12192.474
27.00	99995	74022	3570407	10708.071
28.00	100202	74159	3569672	10747.889
29.00	106094	77859	3539619	11847.138
30.00	112983	81695	3487577	13043.231

Table 6.20 Suboptimal time paths for species 1: Plaice

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	232700	21100	1787891	23364.462
1.00	857	0.00	0.00	0.000
2.00	0.00	0.00	0.00	0.000
3.00	0.00	0.00	0.00	0.000
4.00	0.00	0.00	0.00	0.000
5.00	0.00	0.00	0.00	0.000
6.00	0.00	0.00	0.00	0.000
7.00	0.00	0.00	0.00	0.000
8.00	0.00	0.00	0.00	0.000
9.00	0.00	0.00	0.00	0.000
10.00	0.00	0.00	0.00	0.000
11.00	0.00	0.00	0.00	0.000
12.00	0.00	0.00	0.00	0.000
13.00	0.00	0.00	0.00	0.000
14.00	0.00	0.00	0.00	0.000
15.00	0.00	0.00	0.00	0.000
16.00	0.00	0.00	0.00	0.000
17.00	0.00	0.00	0.00	0.000
18.00	0.00	0.00	0.00	0.000
19.00	0.00	0.00	0.00	0.000
20.00	0.00	0.00	0.00	0.000
21.00	0.00	0.00	0.00	0.000
22.00	0.00	0.00	0.00	0.000
23.00	0.00	0.00	0.00	0.000
24.00	0.00	0.00	0.00	0.000
25.00	0.00	0.00	0.00	0.000
26.00	0.00	0.00	0.00	0.000
27.00	0.00	0.00	0.00	0.000
28.00	0.00	0.00	0.00	0.000
29.00	0.00	0.00	0.00	0.000
30.00	0.00	0.00	0.00	0.000

Table 6.21 Suboptimal time paths for species 2: C.Sole

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	1475900	346300	992834	53555.322
1.00	1136482	473209	1761862	15.466
2.00	476825	432742	3840175	14.044
3.00	163588	149623	3870134	25906.380
4.00	86332	58697	2876879	3988.001
5.00	69549	24474	1489012	0.738
6.00	68804	19297	1186753	0.581
7.00	68926	20149	1236975	0.607
8.00	69147	21690	1327299	0.653
9.00	69166	21828	1335339	0.658
10.00	69249	22403	1368884	0.675
11.00	70282	29453	1773268	0.889
12.00	71776	39299	2316808	1.188
13.00	73513	50246	2892116	1.522
14.00	75061	59569	3358082	1.807
15.00	76302	66773	3702955	2.028
16.00	77420	73065	3993362	2.222
17.00	77510	73567	4016092	2.238
18.00	75047	59491	3354267	1.805
19.00	71978	40602	2386868	1.227
20.00	72557	44286	2582685	1.340
21.00	74534	56440	3204133	1.711
22.00	76006	65076	3622899	1.976
23.00	76405	67363	3730597	2.047
24.00	75472	61985	3475194	1.881
25.00	73828	52172	2990216	1.581
26.00	73317	49038	2830151	1.485
27.00	74138	54057	3085263	1.638
28.00	75158	60144	3386101	1.825
29.00	75665	63105	3528992	1.916
30.00	75397	61547	3454080	1.868

Table 6.22 Suboptimal time paths for species 3: Cod

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	378700	231200	825091	51908.169
1.00	171775	0.00	0.00	0.000
2.00	31742	0.00	0.00	0.000
3.00	16285	0.00	0.00	0.000
4.00	12061	0.00	0.00	0.000
5.00	9457	0.00	0.00	0.000
6.00	8411	0.00	0.00	0.000
7.00	8944	0.00	0.00	0.000
8.00	11147	0.00	0.00	0.000
9.00	16160	0.00	0.00	0.000
10.00	27211	0.00	0.00	0.000
11.00	33558	19084	768543	-0.014
12.00	33420	13462	544390	-0.007
13.00	33200	4407	179401	-0.001
14.00	31889	0.00	0.00	0.000
15.00	25363	0.00	0.00	0.000
16.00	17440	0.00	0.00	0.000
17.00	11012	0.00	0.00	0.000
18.00	7461	0.00	0.00	0.000
19.00	6658	0.00	0.00	0.000
20.00	7247	0.00	0.00	0.000
21.00	7348	0.00	0.00	0.000
22.00	6205	0.00	0.00	0.000
23.00	4585	0.00	0.00	0.000
24.00	3347	0.00	0.00	0.000
25.00	2732	0.00	0.00	0.000
26.00	2548	0.00	0.00	0.000
27.00	2429	0.00	0.00	0.000
28.00	2136	0.00	0.00	0.000
29.00	1715	0.00	0.00	0.000
30.00	1328	0.00	0.00	0.000

Table 6.23 Suboptimal time paths for species 4: Haddock

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	151000	198600	2606381	22268.216
1.00	391	0.00	0.00	0.000
2.00	0.00	0.00	0.00	0.000
3.00	0.00	0.00	0.00	0.000
4.00	0.00	0.00	0.00	0.000
5.00	0.00	0.00	0.00	0.000
6.00	0.00	0.00	0.00	0.000
7.00	0.00	0.00	0.00	0.000
8.00	0.00	0.00	0.00	0.000
9.00	0.00	0.00	0.00	0.000
10.00	0.00	0.00	0.00	0.000
11.00	0.00	0.00	0.00	0.000
12.00	0.00	0.00	0.00	0.000
13.00	0.00	0.00	0.00	0.000
14.00	0.00	0.00	0.00	0.000
15.00	0.00	0.00	0.00	0.000
16.00	0.00	0.00	0.00	0.000
17.00	0.00	0.00	0.00	0.000
18.00	0.00	0.00	0.00	0.000
19.00	0.00	0.00	0.00	0.000
20.00	0.00	0.00	0.00	0.000
21.00	0.00	0.00	0.00	0.000
22.00	0.00	0.00	0.00	0.000
23.00	0.00	0.00	0.00	0.000
24.00	0.00	0.00	0.00	0.000
25.00	0.00	0.00	0.00	0.000
26.00	0.00	0.00	0.00	0.000
27.00	0.00	0.00	0.00	0.000
28.00	0.00	0.00	0.00	0.000
29.00	0.00	0.00	0.00	0.000
30.00	0.00	0.00	0.00	0.000

Table 6.24 Suboptimal time paths for species 5: Saithe

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	380400	108800	1626008	9957.648
1.00	1593391	634449	2263646	-17.603
2.00	1234723	620430	2856654	-16.834
3.00	666600	567354	4838635	-14.077
4.00	672416	568351	4805216	-14.127
5.00	759957	581524	4350240	-14.789
6.00	791037	585500	4207888	-14.992
7.00	800701	586673	4165430	-15.052
8.00	831163	590193	4036842	-15.233
9.00	863268	593633	3909368	-15.411
10.00	890557	596363	3807001	-15.553
11.00	1020148	540045	3009545	8933.413
12.00	1284006	622821	2757593	-16.964
13.00	1660417	636397	2178939	-17.712
14.00	2029175	644813	1806543	-18.183
15.00	2286206	649073	1614033	-18.424
16.00	2458471	651430	1506388	-18.558
17.00	2520906	652205	1470826	-18.602
18.00	2318736	649545	1592546	-18.451
19.00	1918819	642633	1903985	-18.060
20.00	1794931	639867	2026638	-17.905
21.00	1984420	643958	1844838	-18.135
22.00	2228628	648204	1653516	-18.375
23.00	2351066	650001	1571750	-18.477
24.00	2298680	649256	1605726	-18.435
25.00	2111812	646296	1739843	-18.267
26.00	1976233	643798	1852019	-18.126
27.00	2013144	644511	1820076	-18.166
28.00	2143833	646839	1715299	-18.298
29.00	2245711	648467	1641602	-18.390
30.00	2253532	648585	1636205	-18.397

Table 6.25 Suboptimal time paths for species 6: Whiting

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	675200	608300	11911551	28822.979
1.00	5615630	944340	2223377	37.678
2.00	9345353	951189	1345718	38.226
3.00	6047106	945565	2067411	37.775
4.00	5351285	943493	2331113	37.610
5.00	4789560	941381	2598679	37.442
6.00	3960802	937171	3128373	37.108
7.00	3094851	930363	3974619	36.571
8.00	2261421	918887	5372341	35.674
9.00	1418636	893570	8327997	33.735
10.00	679589	409848	7973687	37801.926
11.00	177555	82877	6171398	6263.360
12.00	13221	0.00	0.00	0.000
13.00	82	0.00	0.00	0.000
14.00	0.00	0.00	0.00	0.000
15.00	0.00	0.00	0.00	0.000
16.00	0.00	0.00	0.00	0.000
17.00	0.00	0.00	0.00	0.000
18.00	0.00	0.00	0.00	0.000
19.00	0.00	0.00	0.00	0.000
20.00	0.00	0.00	0.00	0.000
21.00	0.00	0.00	0.00	0.000
22.00	0.00	0.00	0.00	0.000
23.00	0.00	0.00	0.00	0.000
24.00	0.00	0.00	0.00	0.000
25.00	0.00	0.00	0.00	0.000
26.00	0.00	0.00	0.00	0.000
27.00	0.00	0.00	0.00	0.000
28.00	0.00	0.00	0.00	0.000
29.00	0.00	0.00	0.00	0.000
30.00	0.00	0.00	0.00	0.000

Table 6.26 Suboptimal time paths for species 7: Herring

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	501400	92400	1605821	3280.555
1.00	829082	0.00	0.00	0.000
2.00	140373	0.00	0.00	0.000
3.00	28074	0.00	0.00	0.000
4.00	11107	0.00	0.00	0.000
5.00	5237	0.00	0.00	0.000
6.00	2816	0.00	0.00	0.000
7.00	1835	0.00	0.00	0.000
8.00	1475	0.00	0.00	0.000
9.00	1444	0.00	0.00	0.000
10.00	1711	0.00	0.00	0.000
11.00	2428	0.00	0.00	0.000
12.00	3983	0.00	0.00	0.000
13.00	7200	0.00	0.00	0.000
14.00	13986	0.00	0.00	0.000
15.00	28610	0.00	0.00	0.000
16.00	51385	39760	6742551	-0.002
17.00	51371	39207	6650552	-0.002
18.00	51228	33365	5675286	-0.001
19.00	51075	27094	4622391	-0.001
20.00	51138	29671	5055885	-0.001
21.00	51250	34251	5823564	-0.001
22.00	51317	37017	6285635	-0.002
23.00	51326	37371	6344586	-0.002
24.00	51269	35024	5952891	-0.001
25.00	51183	31513	5365119	-0.001
26.00	51169	30944	5269679	-0.001
27.00	51221	33094	5630054	-0.001
28.00	51273	35216	5984852	-0.001
29.00	51293	36017	6118632	-0.002
30.00	51273	35190	5980567	-0.001

Table 6.27 Suboptimal time paths for species 8: Sprat

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	527900	182200	26520757	2837.833
1.00	879740	744270	65007770	0.020
2.00	12087968	1157598	7358574	0.049
3.00	8546823	1144156	10286553	0.047
4.00	6519605	1129889	13316919	0.046
5.00	7200659	1135578	12118087	0.047
6.00	8353144	1143093	10515274	0.047
7.00	8744730	1145195	10062878	0.047
8.00	9124951	1147064	9659311	0.048
9.00	9721097	1149699	9087786	0.048
10.00	10037615	1150971	8810957	0.048
11.00	9193047	1147382	9590422	0.048
12.00	7739921	1139373	11311457	0.047
13.00	6170297	1126484	14028400	0.046
14.00	4935014	1110575	17292142	0.045
15.00	4024207	1092590	20862482	0.043
16.00	3238719	1068955	25361522	0.041
17.00	3486770	1077569	23747123	0.042
18.00	5732548	1121631	15034583	0.046
19.00	8036674	1141244	10911672	0.047
20.00	7002654	1134038	12443836	0.047
21.00	5284357	1115829	16225365	0.045
22.00	4265660	1098106	19780950	0.044
23.00	4157354	1095711	20252009	0.043
24.00	5062421	1112575	16887302	0.045
25.00	6375671	1128531	13601190	0.046
26.00	6554293	1130208	13250173	0.046
27.00	5732522	1121630	15034647	0.046
28.00	4942823	1110701	17266774	0.045
29.00	4656667	1105825	18247381	0.044
30.00	4981588	1111318	17141933	0.045

Table 6.28 Suboptimal time paths for species 9: Mackerel

(Fishing Effort in '000TH)

TIME	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
0.00	6370100	1019900	2196170	132969.568
1.00	13158	0.00	0.00	0.000
2.00	0.00	0.00	0.00	0.000
3.00	0.00	0.00	0.00	0.000
4.00	0.00	0.00	0.00	0.000
5.00	0.00	0.00	0.00	0.000
6.00	0.00	0.00	0.00	0.000
7.00	0.00	0.00	0.00	0.000
8.00	0.00	0.00	0.00	0.000
9.00	0.00	0.00	0.00	0.000
10.00	0.00	0.00	0.00	0.000
11.00	0.00	0.00	0.00	0.000
12.00	0.00	0.00	0.00	0.000
13.00	0.00	0.00	0.00	0.000
14.00	0.00	0.00	0.00	0.000
15.00	0.00	0.00	0.00	0.000
16.00	0.00	0.00	0.00	0.000
17.00	0.00	0.00	0.00	0.000
18.00	0.00	0.00	0.00	0.000
19.00	0.00	0.00	0.00	0.000
20.00	0.00	0.00	0.00	0.000
21.00	0.00	0.00	0.00	0.000
22.00	0.00	0.00	0.00	0.000
23.00	0.00	0.00	0.00	0.000
24.00	0.00	0.00	0.00	0.000
25.00	0.00	0.00	0.00	0.000
26.00	0.00	0.00	0.00	0.000
27.00	0.00	0.00	0.00	0.000
28.00	0.00	0.00	0.00	0.000
29.00	0.00	0.00	0.00	0.000
30.00	0.00	0.00	0.00	0.000

Table 6.29 Suboptimal time paths for species 10: Others

(Fishing Effort in '000TH)

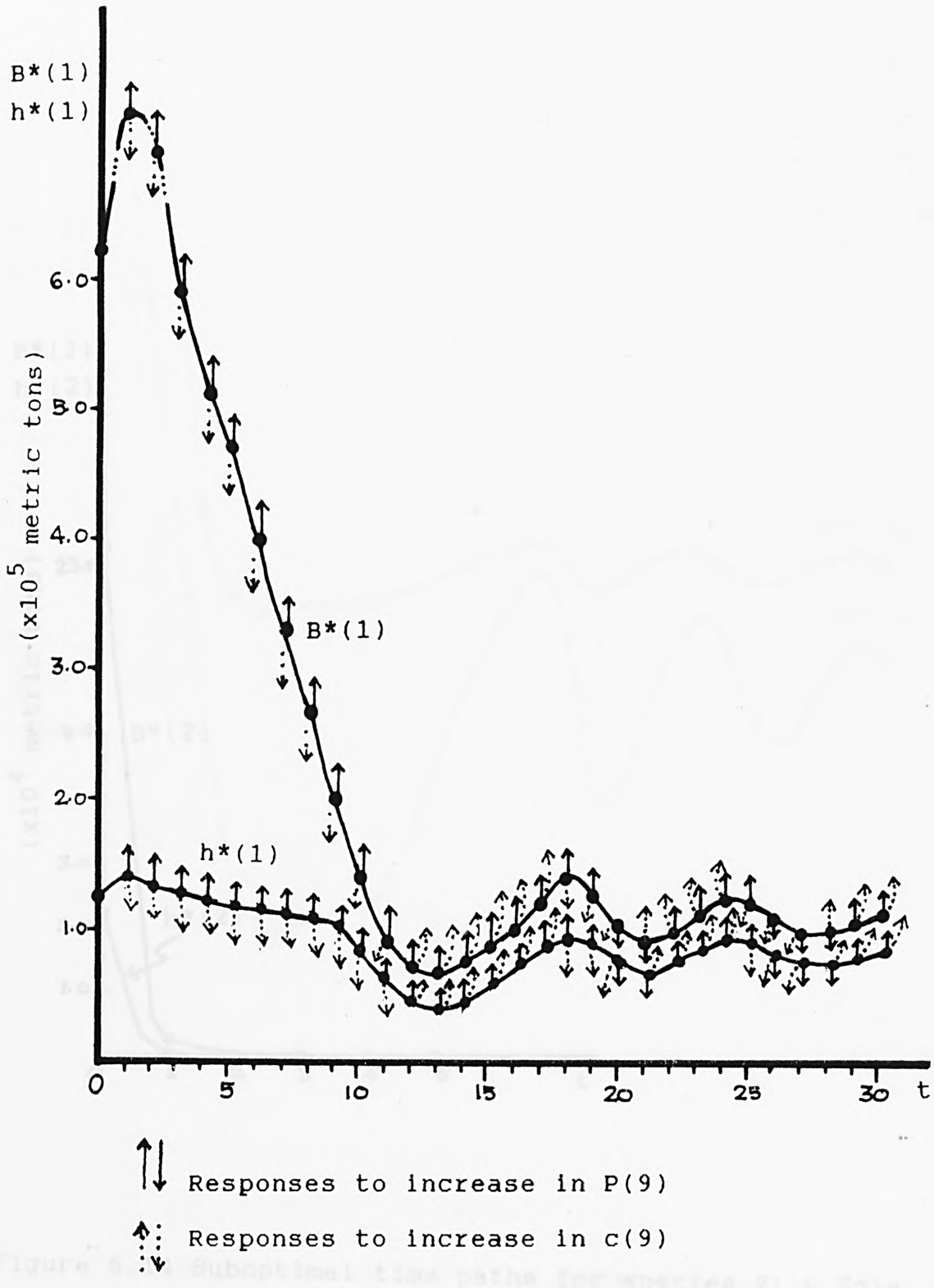


Figure 6.13 Suboptimal time paths for species 1: Plaice (fishing effort in '000TH)



Figure 6.14 Suboptimal time paths for species 2: C.Sole (fishing effort in '000TH)

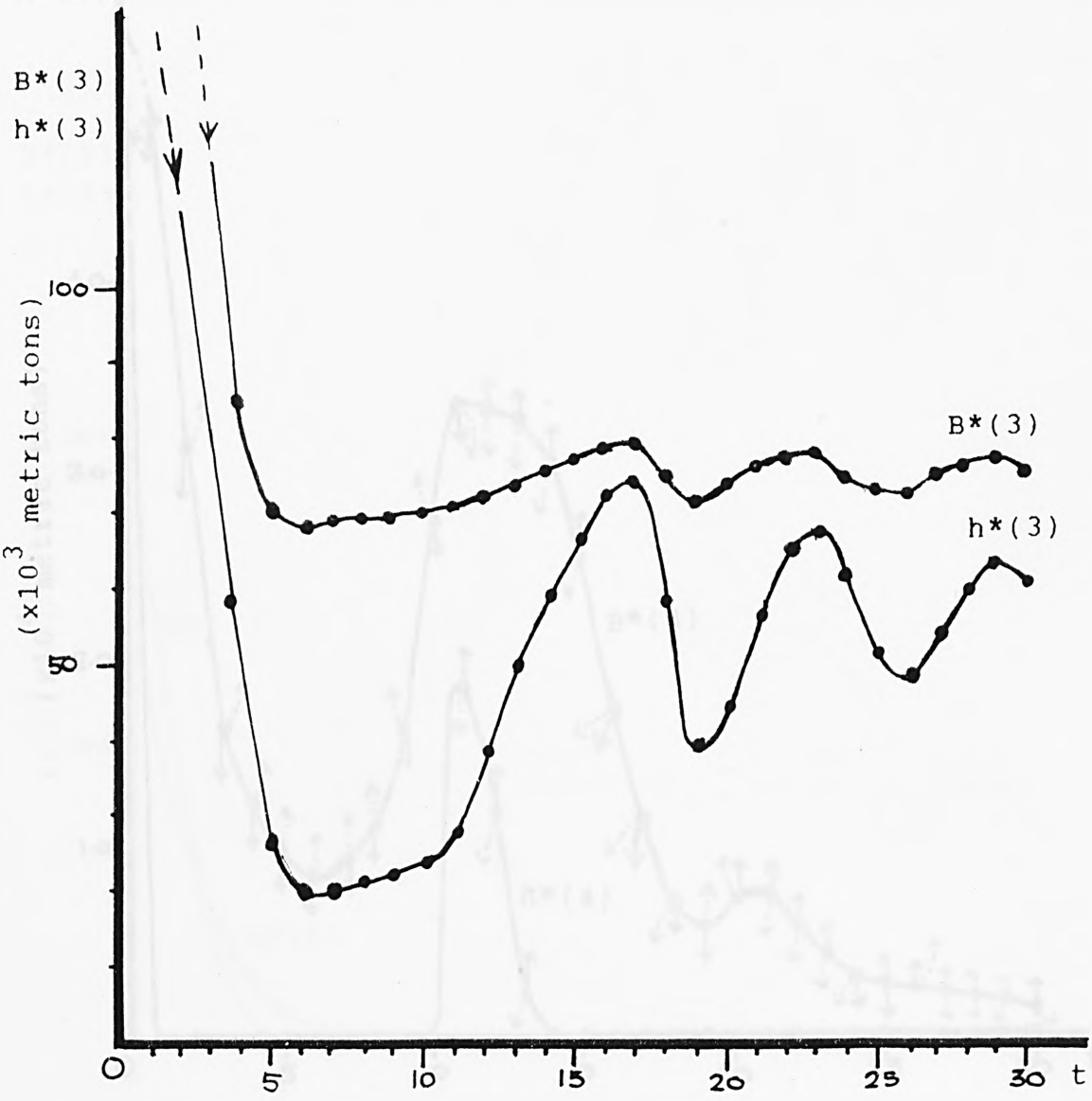


Figure 6.15 Suboptimal time paths for species 3: Cod (fishing effort in '000TH)

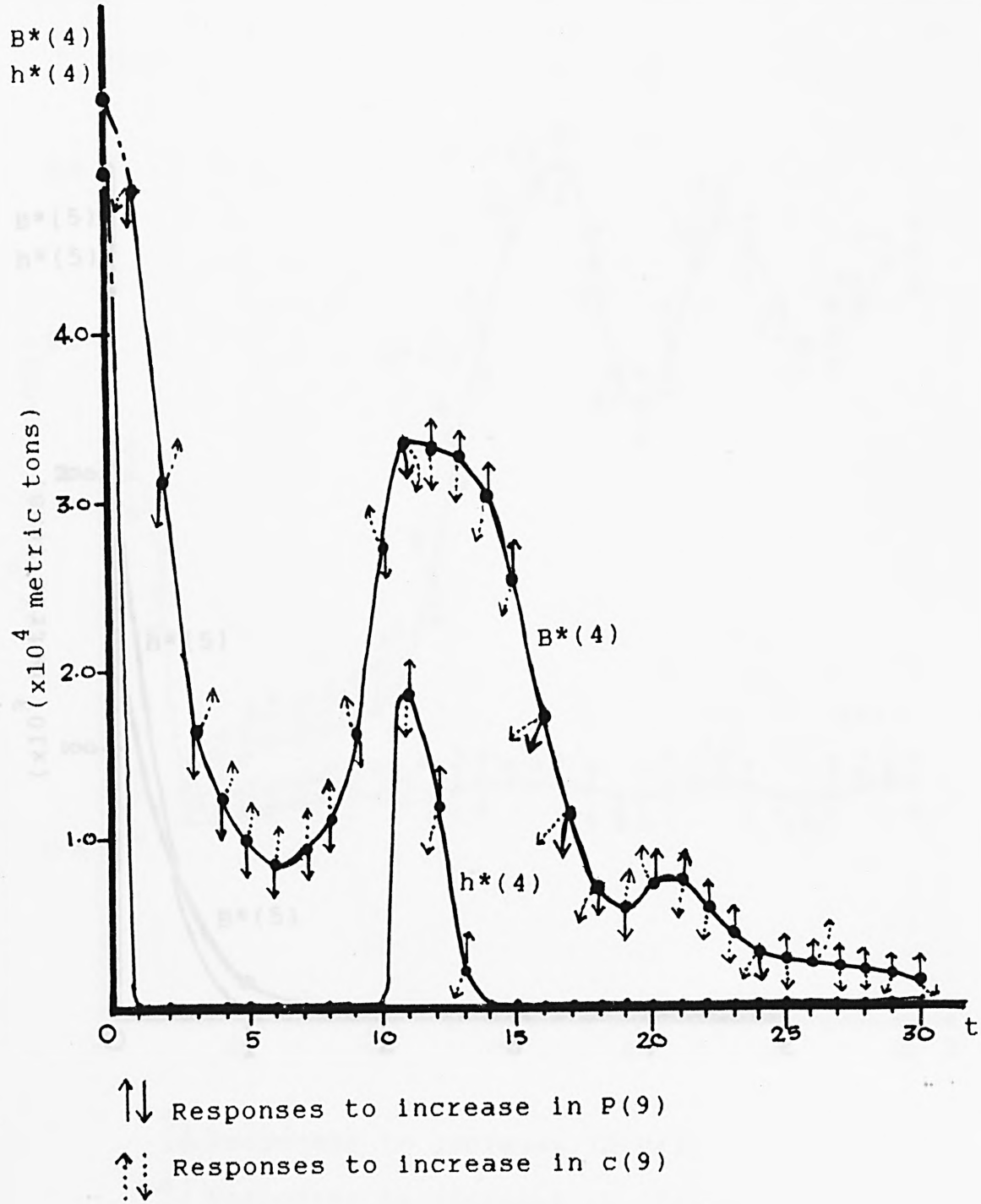


Figure 6.16 Suboptimal time paths for species 4: Haddock (fishing effort in '000TH)

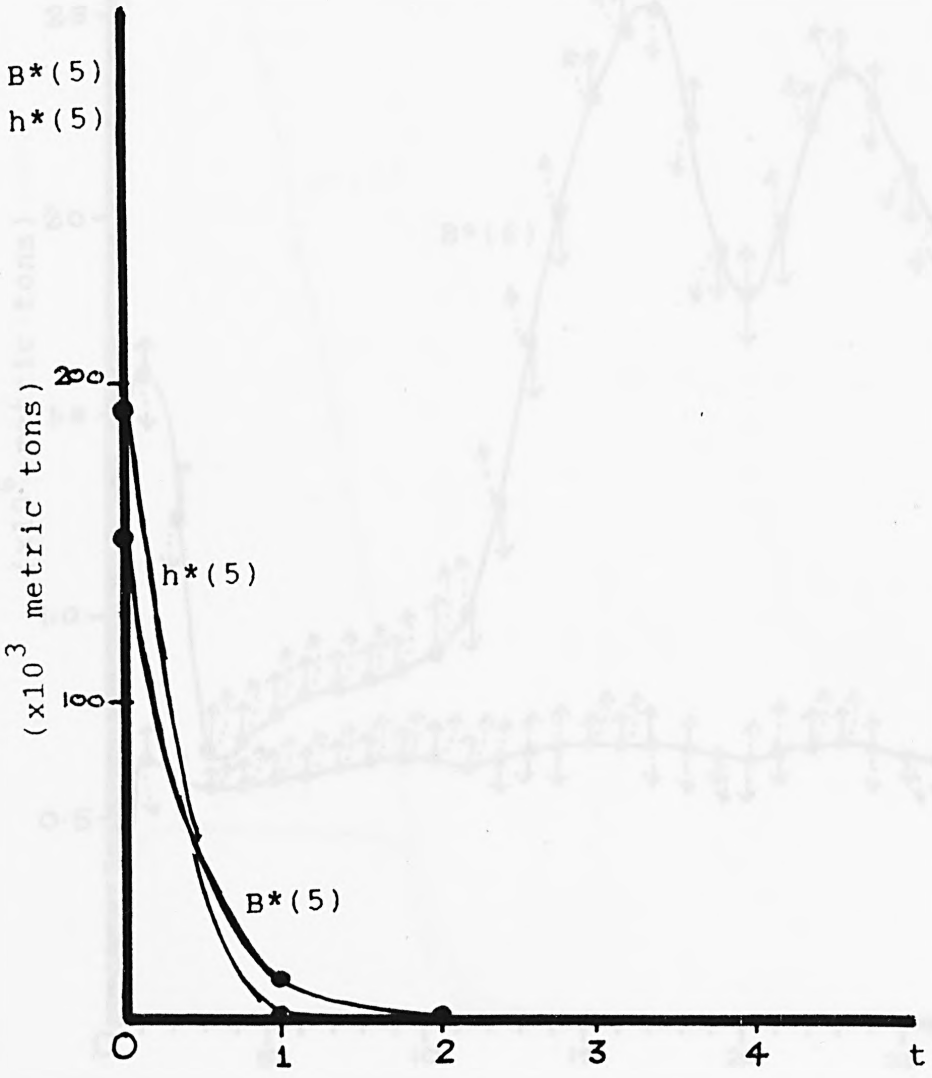


Figure 6.17 Suboptimal time paths for species 5: Saithe (fishing effort in '000TH)

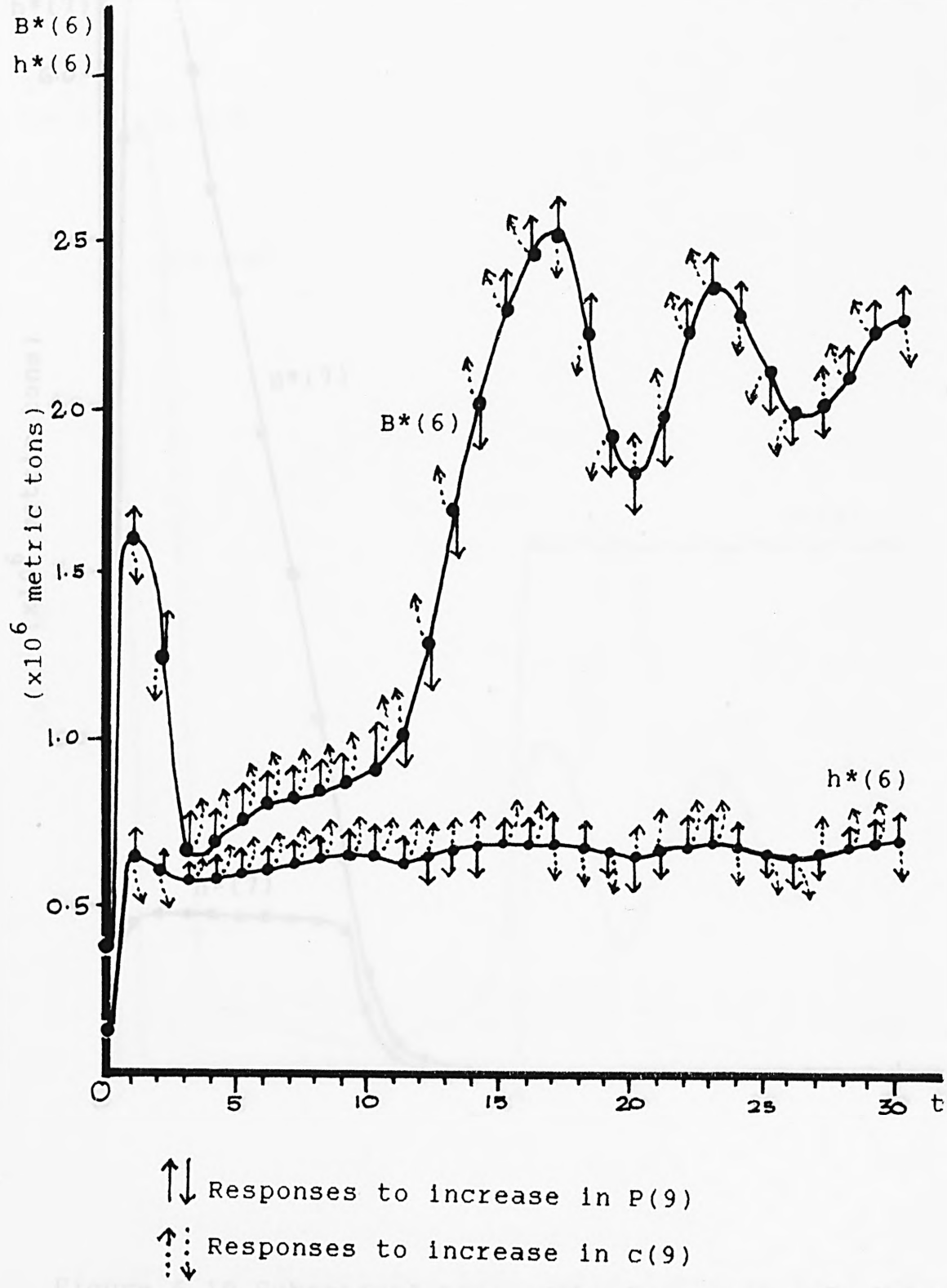


Figure 6.18 Suboptimal time paths for species 6: Whiting (fishing effort in '000TH)

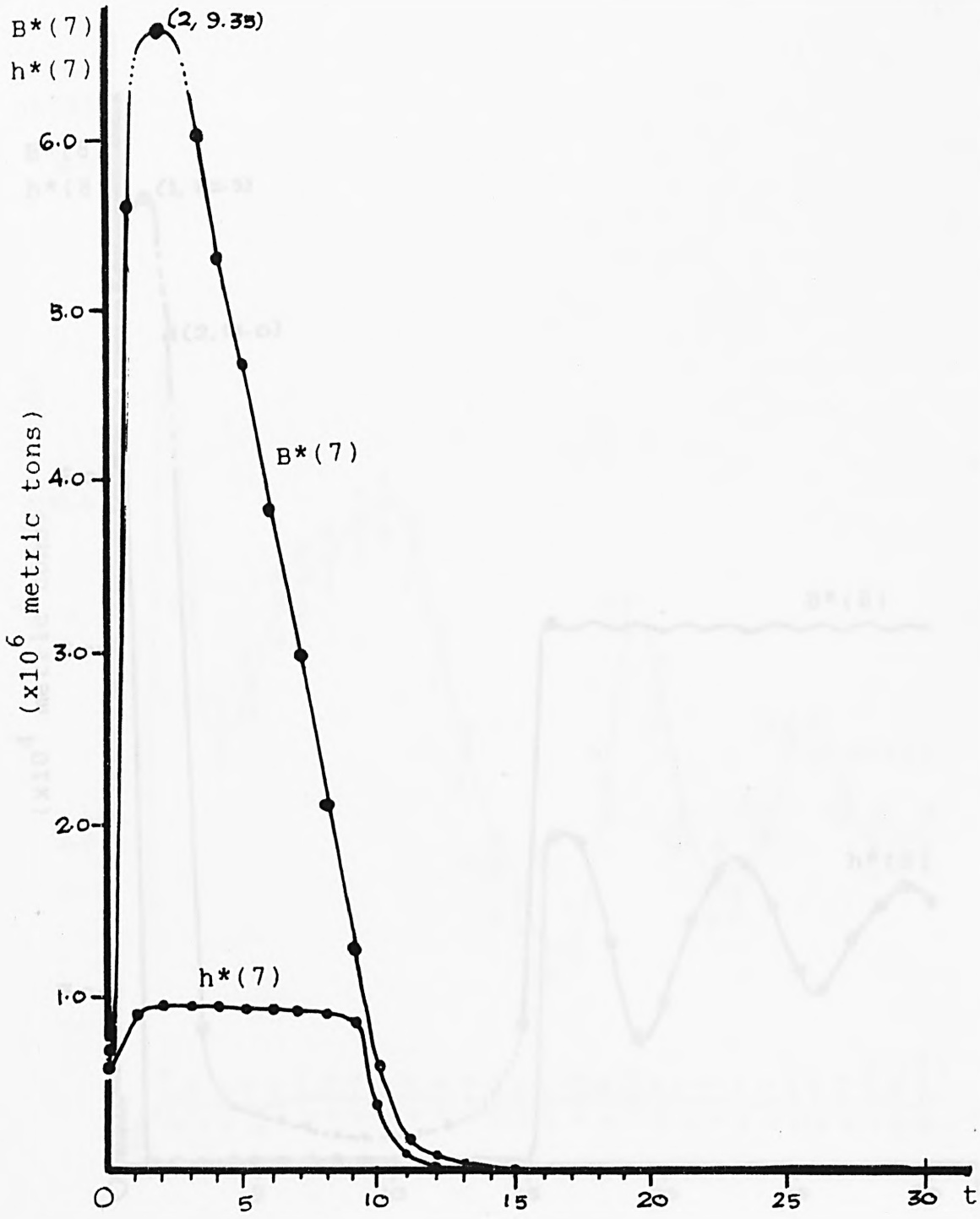


Figure 6.19 Suboptimal time paths for species 7: Herring (fishing effort in '000TH)

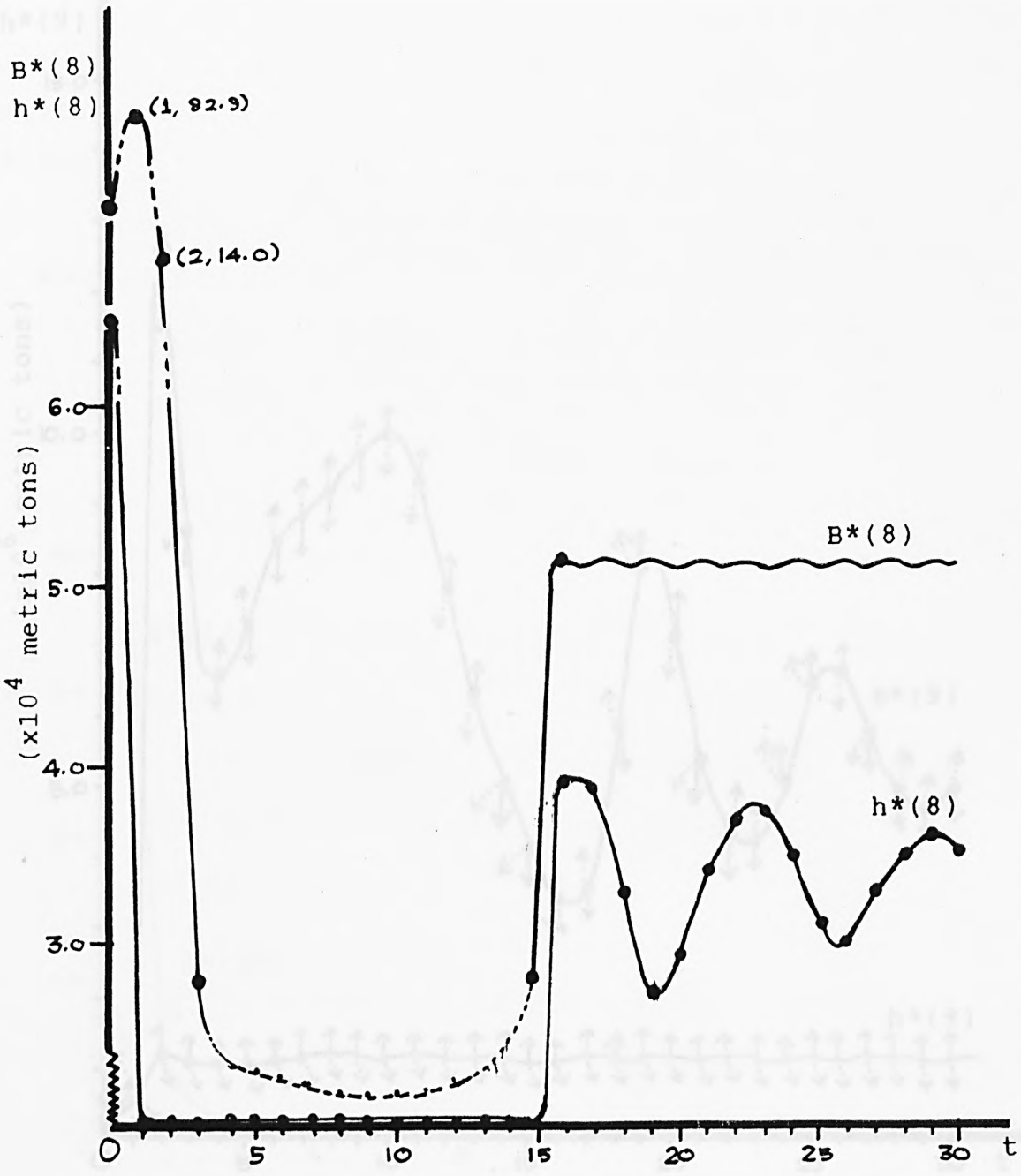


Figure 6.20 Suboptimal time paths for species 8: Sprat (fishing effort in '000TH)

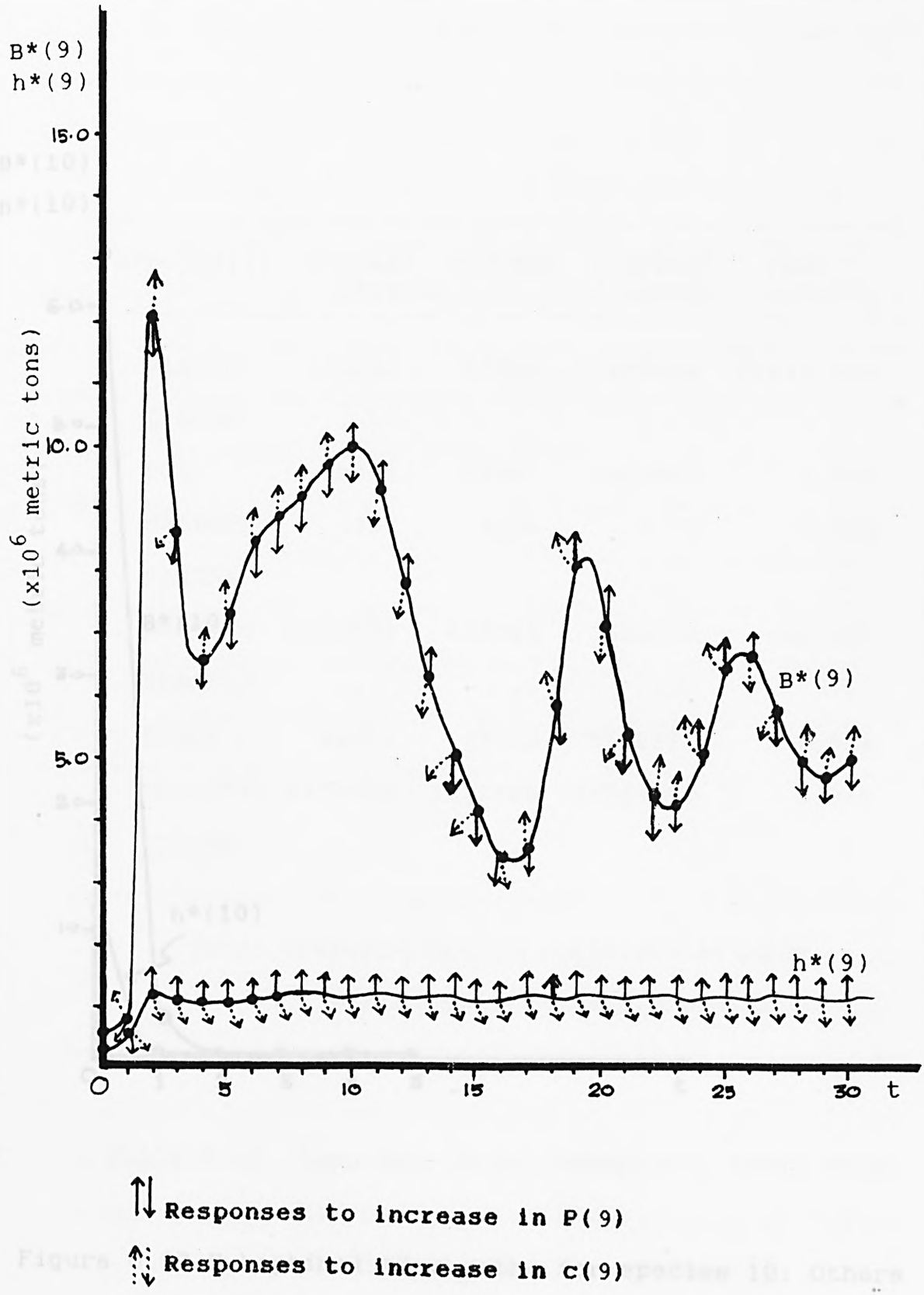


Figure 6.21 Suboptimal time paths for species 9: Mackerel (fishing effort in '000TH)

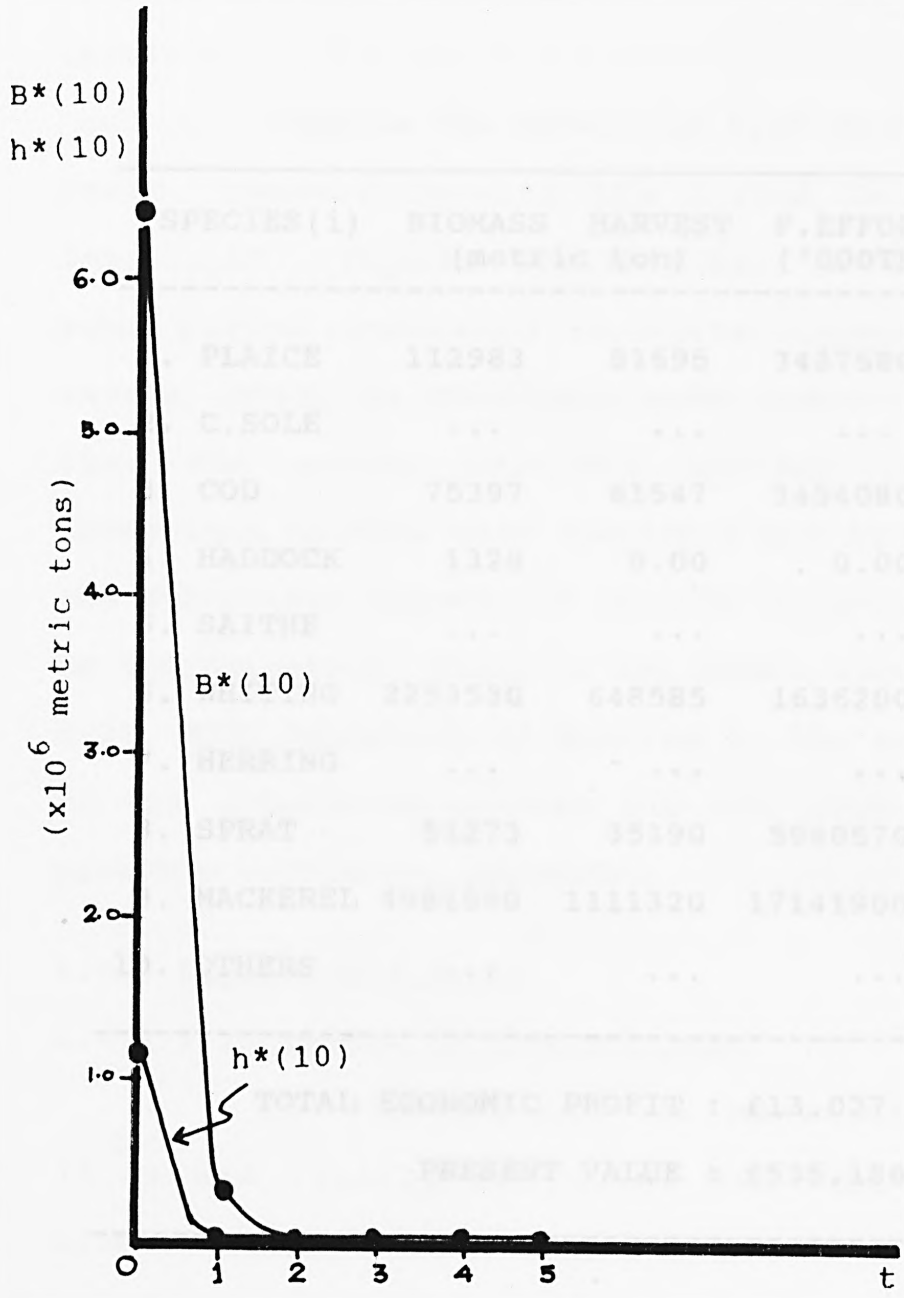


Figure 6.22 Suboptimal time paths for species 10: Others (fishing effort in '000TH)

SPECIES(i)	BIOMASS (metric ton)	HARVEST	F.EFFORT ('000TH)	PROFIT (£'000)
1. PLAICE	112983	81695	3487580	13043.200
2. C.SOLE	...	...	...	...
3. COD	75397	61547	3454080	1.868
4. HADDOCK	1328	0.00	0.00	0.000
5. SAITHE	...	...	...	...
6. WHITING	2253530	648585	1636200	-18.397
7. HERRING	...	...	...	...
8. SPRAT	51273	35190	5980570	-0.001
9. MACKEREL	4981590	1111320	17141900	0.045
10. OTHERS	...	...	...	...

TOTAL ECONOMIC PROFIT : £13.027 MILLION

PRESENT VALUE : £535.186 MILLION

Table 6.30 Long run (t=30) suboptimal level when discount rate is 7.5%

(Fishing Effort in '000TH)

0.70. The proportion of fish harvested every year was thus relatively high despite the relatively low stock level.

Despite the generally high fishing mortality rates, comparison with the actual harvests, h(i), i=1,...,10 (figures 6.3 to 6.12) for the first ten-year period indicated that the suboptimal harvest levels, h*(i) in this case were generally much lower than the actual recorded harvest levels, h(i). Exceptions to this were species 6 and species 9, while the suboptimal harvest of species 1, h*(1) appeared to be approximately close to the actual recorded harvest, h(1). With exception of species 7, the actual harvests of the eliminated species did not seem to suggest a probable future low harvests.

6.6.2 Sensitivity Tests

6.6.2.1 Increases in discount rate

The discount rate was increased from 7.5% to 15.0% and finally to 30.0%. The responses in the biomass and harvest in any period varied from species to species. In some periods, some of the species showed reductions in the levels of their biomasses and harvests while the biomasses and harvests of other species increased. And in some other periods, the reverse occured. As a result responses by the fishing effort also remained unpredictable. This is not surprising since the original optimal solutions were mostly periodic in nature.

Table 6.31 summarises the unpredictable responses at t = 30 when the discount rate was increased to 15.0% and 30.0%. In both cases, the biomass and harvest of species 1 and species 9 showed reductions in their respective levels, followed by increases in the corresponding levels of fishing effort. An opposite pattern of response — increases in biomass and harvest — was exhibited by other species. The relatively low biomass level of species 3 and species 8, however indicated increases in the levels of their fishing efforts. The increase in the relatively high biomass of species 9 was followed by the expected decrease in the level of fishing effort directed at it.

Since the total annual profit was mainly generated from the harvesting of species 1, its value decreased slightly to about £12.970 million and £12.951 million for the respective discount rates. The present value also decreased to about £407.764 million and £308.037 million.

6.6.2.2 Increase in unit price

Inspection of the suboptimal solutions suggests that the sensitivity tests are best done by considering changes in the parameters associated with species 9.

The price (demand) curve of species 9 was shifted by 30.0% from

$$P(9,t) = 69.953 - 5.8782(10^{-5})h(9,t), \quad (6.28)$$

to

$$P(9,t) = 90.939 - 5.8782(10^{-5})h(9,t). \quad (6.29)$$

SPECIES(i)	BIOMASS (metric ton)	HARVEST (metric ton)	F.EFFORT ('000TH)	PROFIT (£'000)
1. PLAICE	112645 (112532)	81518 (81459)	3490450 (3491400)	1298.670 (1296.780)
2. C.SOLE	...	...	...	...
3. COD	75428 (75438)	61726 (61780)	3462700 (3465320)	1.873 (1.875)
4. HADDOCK	1340 (1344)	0.00 (0.00)	0.00 (0.00)	0.000 (0.000)
5. SAITHE	...	...	...	...
6. WHITING	2255230 (2255700)	648611 (648618)	1635040 (1634720)	-18.398 (-18.398)
7. HERRING	...	...	...	...
8. SPRAT	51275 (51275)	35267 (35291)	5993500 (5997510)	-0.001 (-0.001)
9. MACKEREL	4951790 (4942540)	1110840 (1110700)	17267700 (17267700)	0.045 (0.045)
10. OTHERS	...	...	...	...

TOTAL ECONOMIC PROFIT : £12.970 MILLION
(£12.951 MILLION)

PRESENT VALUE : £407.764 MILLION
(£308.037 MILLION)

Note: Figures in brackets refer to the case when the discount rate was increased to 30.0%.

Table 6.31 Long run (t=30) suboptimal level when discount rate is 15.0% (30.0%)
(Fishing Effort in '000TH)

This shift induced an increase in the harvest of species 9 for all t > 2.0. The fishing effort directed at it also increased during that same period. As a result the stock level decreased except at times t = 10-13, 19-20 and 24-26. At most of these times the biomass was decreasing, i.e dB(9,t)/dt < 0. A complete picture of these responses by the biomass and harvest are illustrated in figure 6.21.

At t = 30 years, the equilibrium was established at a lower stock level of about 4.943 million metric tons, a higher harvest level of about 1.468 million metric tons and also a higher fishing effort level of about 22814 million ton-hours fishing.

Species 9 was being preyed by species 4. Thus we would expect the stock of species 4 to adjust to changes in the stock of species 9. Inspections of figures 6.16 and 6.21, however suggested that this adjustment by species 4 was not simultaneous with changes in species 9. On average, it took about two years for species 4 to respond to changes in species 9. Thus a decrease in the stock level of species 9 was followed by a decrease in the stock level of species 4 about two years later. And similarly when the stock level of species 9 increased, the stock level of species 4 only showed an increase about two years later. The harvest of species 4 (only in the interval 11 < t < 13) increased due to the increased biomass. The fishing effort showed an increase in its level

whenever the harvest was not zero. These lagging responses are depicted in figure 6.16. The equilibrium at t = 30 suggested a higher biomass level of about 1412 metric tons due to the lagging response to an increase in the biomass of its prey, species 9 at t = 24-26. The levels of the harvest and the fishing effort remained unchanged at zero. It should be noted that the original suboptimal policy called for a slow elimination of species 4, and hence its relatively low stock level.

Species 1 was a prey to species 9. The higher is the stock level of species 9, the lower should the stock level of species 1 be. Thus, changes in the stock level of species 9 would induce a negative response in the stock level of species 1. As with species 4, species 1 in the long run exhibited a time-lag of about 1-2 years in response to changes in species 9. The changes in its harvest followed closely the changes in its biomass — increased whenever the biomass increased, and decreased whenever the biomass decreased. The fishing effort directed at it in general decreased except at times when the biomass decreased. Figure 6.13 gives a complete picture of these responses by the biomass and the harvest. Despite the lagging response, the biomass at t = 30 was at a higher level of about 121890 metric tons with a higher harvest level of about 86000 metric tons and a lower level of fishing effort at about 3404 million ton-hours fishing.

Except for the three mutually symbiotic species which were eliminated in the early years, the remaining four species all indicated a competitive type of species interaction with species 9. The first, species 3 suggested a periodic suboptimal time paths for its biomass as well as its harvest. Species 6 on the other hand suggested an approximately steady harvest with a long run damped periodic suboptimal biomass. Species 7 only survived for the first thirteen years while significant contributions from species 8 only started after the complete elimination of species 7. It thus seems appropiate to consider responses by species 6 in examining the responses associated with the competitive type of species interaction.

The biomass of species 6 in general increased a year after the decrease in the biomass of its competitor, species 9. Its harvest responded closely to the changes in its biomass. This was followed by an opposite response by the fishing effort directed at it. These expected responses by the biomass and the harvest are captured in figure 6.18. The long run equilibrium (at t = 30) was established at a higher biomass and harvest levels of about 2.297 million metric tons and 649000 metric tons respectively, and a lower level of fishing effort at about 1607 million ton-hours fishing.

Following the complete elimination of species 2, species 5 and species 10 at such an early time, no sensitivity test was possible for the symbiotic type of

SPECIES	t=5.0	t=10.0	t=20.0	t=30.0
SPE.9				
B(9)	7138910	10090400	7281250	4943490
h(9)	1492120	1508190	1493200	1467730
E(9)	16060600	11485100	15757900	22813900
PREDATOR				
B(4)	8394	21804	7537	1412
h(4)	0.00	0.00	0.00	0.00
E(4)	0.00	0.00	0.00	0.00
PREY				
B(1)	479044	144316	98625	121890
h(1)	126843	94523	73094	86013
E(1)	1277110	3159090	3574660	3403560
COMP. CASE				
B(6)	773044	894558	1711960	2296530
h(6)	583237	596749	637791	649224
E(6)	4289190	3792430	2117970	1607150

Table 6.32 Sensitivity tests for increase in unit price of species 9 (Fishing Effort in '000TH)

species interaction.

6.6.2.3 Increase in the unit cost

The unit cost of harvesting of species 9, c(9) was increased by 30.0% from £0.30 to £0.39 per thousand ton-hours fishing.

This caused a reduction in the level of the harvest of species 9 for all t > 1.0, followed by an increase in the stock level except at times when its rate of change, dB(9,t)/dt was negative. The response in fishing effort followed opposite changes in the biomass, decreasing (increasing) whenever the biomass increased (decreased). Figure 6.21 gives a complete picture of these responses by the biomass and the harvest. The long run bioeconomic equilibrium level (at t = 30) was established at a higher biomass level of about 5.115 million metric tons, a slightly lower harvest level of about 1.090 million metric tons and a lower fishing effort level of about 16390 million ton-hours fishing.

Following increases in the stock of species 9, the stock of its predator, species 4 also increased but with a time lag of about 1-2 years. The harvest of species 4 and the level of fishing effort directed at it, whenever feasible, responded accordingly to changes in its biomass. A complete picture of responses by the biomass and harvest are depicted in figure 6.16. Due to the lagging effect, the stock level at t = 30 decreased

to about 1279 metric tons while the harvest and fishing effort remained unfeasible at zero level.

Responses associated with the prey, species 1 also exhibited some lagging of about two years. The biomass thus in general decreased (increased) two years after the biomass of species 9 increased (decreased). As before, the harvest closely followed the changes in its own biomass. The fishing effort on the other hand fluctuated in the opposite direction to fluctuations in the biomass. These lagging responses by the biomass and the harvest are depicted in figure 6.13. At $t = 30$, the stock level indicated a slight increase to about 113461 metric tons, followed by a slight increase in the harvest level to about 81945 metric tons and a slight decrease in the level of fishing effort to about 3483 million ton-hours fishing.

Despite increases in the stock level of species 9, the stock level of its competitor, species 6 and its harvest seemed to increase in the short run ($3 < t < 16$). Species 6, however was also preying on species 4, whose biomass also increased in the short run due to the increase in the stock of its prey, species 9. Thus it appeared that despite the competitive nature of their interactions, species 6 seemed to benefit from the abundance of its competitor, species 9. But in the long run, as the stock of species 4 was slowly reduced, the competitive interaction between species 6 and species 9 became more dominant and

SPECIES	t=5.0	t=10.0	t=20.0	t=30.0
SPE.9				
B(9)	7307980	9947940	6617260	5110560
h(9)	1120280	1138790	1113000	1090280
E(9)	11779300	8796310	12924200	16393100
PREDATOR				
B(4)	10758	33481	7457	1279
h(4)	0.00	15955	0.00	0.00
E(4)	0.00	644014	0.00	0.00
PREY				
B(1)	461154	129350	96277	113461
h(1)	126303	89171	71444	81945
E(1)	1321000	3325040	3579140	3483460
COMP. CASE				
B(6)	762480	896770	1816610	2240440
h(6)	581859	596961	640379	648386
E(6)	4338340	3784420	2004060	1645260

Table 6.33 Sensitivity tests for increase in unit cost of harvesting species 9. (Fishing Effort in '000TH)

species 6 responded accordingly — decreased (increased) whenever the stock of its competitor increased (decreased). The harvest and the fishing effort responded accordingly. These responses are summarised in table 6.33 for selected years and depicted in figure 6.18 for the biomass and the harvest. At t = 30, the long run equilibrium was established at a lower stock level of about 2.240 million metric tons, a lower harvest level of about 648400 metric tons and a higher fishing effort level of about 1645 million ton-hours fishing.

As before, no sensitivity test was possible for the symbiotic type of species interaction.

6.7 Summary

In this chapter, the suboptimal time paths associated with the maximization of the present value were determined for each species for both measures of fishing effort subject to suitable bioeconomic constraints on the state and the control variables.

Suboptimality in both cases suggested complete eliminations of some species (but not necessarily the same species), harvesting some species at bioeconomic equilibrium levels, harvesting some species at some economically profitable levels and periodic harvesting of some species.

Responses to changes in the unit price of harvest and unit cost of fishing effort appeared in

general to agree reasonably well with the theoretical analysis discussed in Chapter 4. Although the responses in the first case of fishing effort were quite simultaneous, responses in the second case of fishing effort appeared to lag 1-2 years behind. Also, responses were found to be more conclusive for species exhibiting steady suboptimal paths than those with periodic suboptimal paths.

Although the solutions can be regarded as suboptimal solutions, the profit generated were far from the economically desirable level. From an economist's point of view, dissipation of economic rent (with zero profit) is not a desirable optimum or suboptimum, while biologists would argue that driving some species to extinction is by no mean biologically optimal (or suboptimal).

Thus some form of regulations should be formulated and imposed either directly or indirectly on either the fishing effort or the harvest or both so that in the long run the economic profit remains at some optimal or suboptimal level without calling for the depletion of some species. The various measures and regulations capable of achieving these objectives, at least in principle, are briefly discussed in the next chapter together with its implementations at both the national and international levels.

CHAPTER 7

FISHERY REGULATIONS AND MANAGEMENT

7.1 Introduction

As suggested by the simulation results in the previous chapter, an unregulated open-access fishery can lead to a bioeconomic equilibrium with complete dissipation of economic rent as well as the complete depletion of some species despite the solutions being suboptimal. The expansion to the level of zero profit is normally regarded as economic overfishing implying an inefficient allocation of resources while the second situation is usually associated with biological overfishing.

Thus, some form of regulations need to be employed to ensure that the fishery remains at some profitable level without depleting any of the stocks. It is the objective of this chapter to evaluate the different types of regulations that are normally adopted by the fishery authorities in the management of commercial fisheries. Three criteria are used to assess the effects of these regulations — economic efficiency, flexibility and ease of implementation and enforcement.

The first criterion calls for the capability of the regulations adopted to give the greatest possible net contribution to the economy. In view of the uncertainty of the ecosystems and the importance of

conserving the biological stock, any policy employed by the authority should be sufficiently flexible in the sense that rapid changes can be made to the policy whenever the situation demands so. Finally, the regulation must also have sufficient support and acceptance from the fishing community and other related parties before it can be properly and effectively implemented and enforced.

Various alternative measures of fishery regulations are discussed below. These include the catch quota, licensing scheme, tax on fishing effort, tax on catch, transferable fishing rights as well as other measures such as gear restrictions, closed seasons and closed areas. Fishery managements at national and international levels are also considered with reference to United Kingdom and the European Economic Community (EEC) respectively.

The analysis adopts a single-factor approach using a single species model and a single-factor of production, the fishing effort.

7.2 The Catch Quota

Under the catch quota system the fishery is regulated by permitting the aggregate level of harvest only to the level that is deemed socially desirable by the management authority. It is the most directive means of fishery management and ranks highly in terms of flexibility and implementation. Because of its

simplicity, it is also the most popular and frequently employed by the authority.

Now, consider a fishery which is initially operating at an open-access bioeconomic equilibrium with harvest at level h_{∞} being produced at a total cost of TC_{∞} and generating total revenue TR_{∞} ($=TC_{\infty}$) with complete dissipation of economic rent. Suppose that a catch quota is set at h_Q ($> h_{\infty}$). This level of harvest can only be achieved if the population size is increased. Thus in the early periods the harvest need to be reduced (either by setting a lower quota or temporarily closing the fishery) so as to raise the population which will in turn allow for larger harvest in later periods.

From figure 7.1(a), the corresponding revenue TR_Q (assuming that it is a quadratic function of fishing effort only) for a given population level can be generated by two levels of fishing effort, E_{Q1} and E_{Q2}, ($E_{Q1} < E_{Q2}$), at a total cost of TC_{Q1} and TC_{Q2}, ($TC_{Q1} < TC_{Q2}$) respectively (figure 7.1(b)). Since no constraint is imposed on the fishing effort, both smaller and larger fishing efforts would be feasible, both generating positive economic rents which will in turn attract more units of fishing effort until all the economic rents are again completely dissipated.

Since high unit cost is usually associated with greater technological fishing capacity, fishermen equipped with a high-unit cost of fishing effort will

be in a better position. Thus, in the long run, a new open-access bioeconomic equilibrium is established at Q_1 with fishing effort at level E_{Q1}. The total cost curve now shifts from TC to TC1.

Despite its flexibility and ease of implementation, the catch quota system is not effective in controlling fishing activity at the desired level since it imposes no restriction on fishing effort within the fishing season and no control over the entry of fishermen following the creation of potential profit from fishing. The scheme thus in the long run creates a new open-access bioeconomic equilibrium with a higher cost of fishing, still falling short of economic efficiency.

The scheme also results in a number of undesirable consequences. Once the total catch quota is set, fishermen not only will be induced to rush fishing but also to expand the fishing capacity of their fishing vessels and/or gears more intensively than before in order to harvest as much and as soon as possible before the quota is reached and the fishery closed. This leads to a higher unit cost of fishing than before as well as shortening the duration of the fishing season since a larger fishing capacity enables the harvest of a given level to be taken in a shorter length of time.

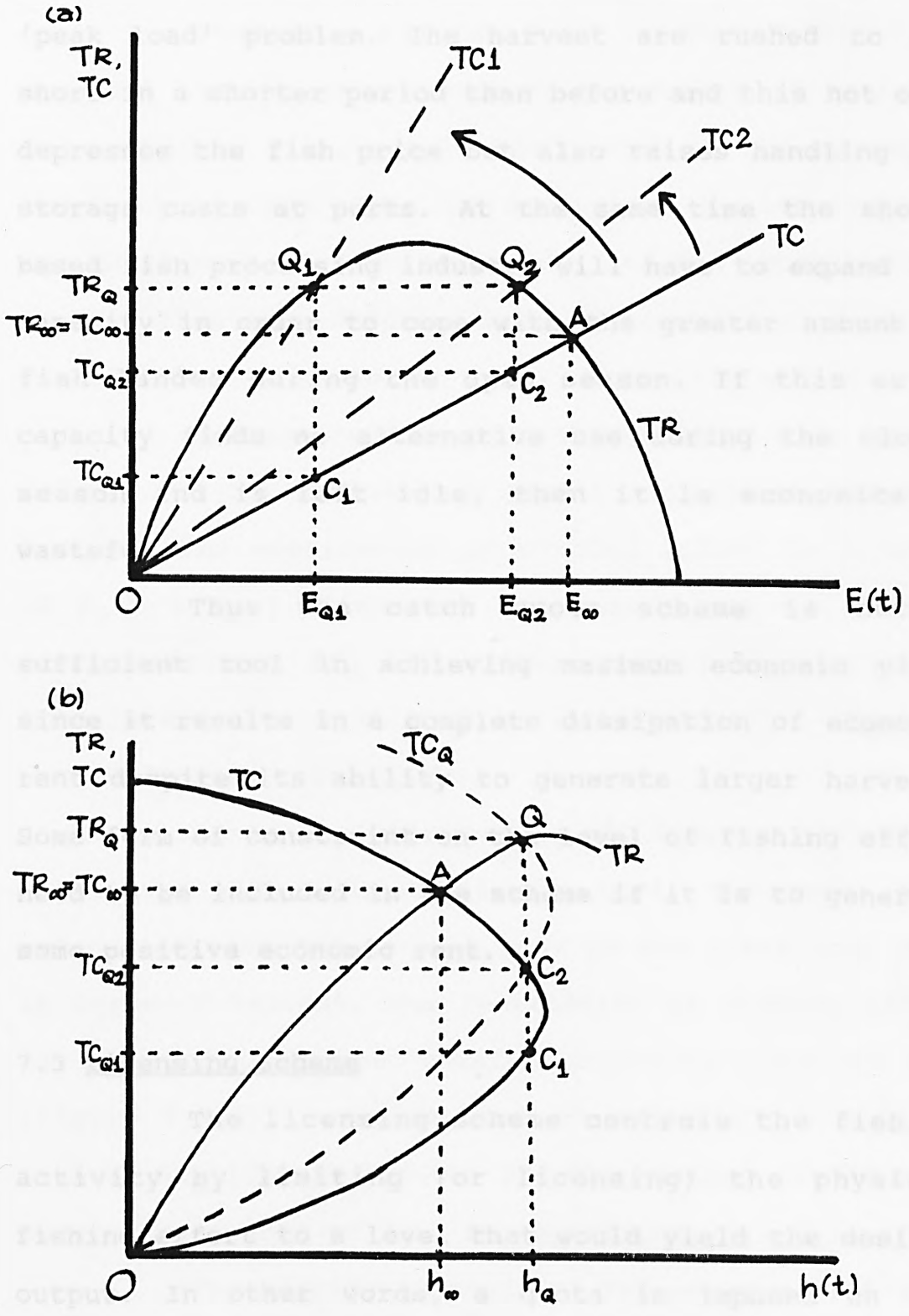


Figure 7.1 The catch quota system

The shorter fishing season in turn creates a 'peak load' problem. The harvest are rushed to the shore in a shorter period than before and this not only depresses the fish price but also raises handling and storage costs at ports. At the same time the shore-based fish processing industry will have to expand its capacity in order to cope with the greater amount of fish landed during the open season. If this extra capacity finds no alternative use during the closed season and is left idle, then it is economically wasteful.

Thus the catch quota scheme is not a sufficient tool in achieving maximum economic yield since it results in a complete dissipation of economic rent despite its ability to generate larger harvest. Some form of constraint on the level of fishing effort need to be included in the scheme if it is to generate some positive economic rent.

7.3 Licensing Scheme

The licensing scheme controls the fishing activity by limiting (or licensing) the physical fishing effort to a level that would yield the desired output. In other words, a quota is imposed on the fishing effort. Since a sudden restriction on fishing effort can result in undesirable economic and social problems, its implementation is normally quite gradual, thereby providing the fishermen and the fishing firms

sufficient time for adjustment.

Consider figure 7.2. Suppose that the physical fishing effort such as the number of boats or the number of fishermen is restricted to the aggregate level of E_o only. This is equivalent to constraining the total cost of fishing to TC_o, and the total revenue to TR_o. Thus only unique levels of revenue and cost are associated with any given level of fishing effort.

Average revenue of fishing effort will be AR_o (figure 7.2(b)) and average profit will be AZ_o (figure 7.2(c)). The restriction of fishing effort to a level of E_o ($< E_o'$) eliminates the possibility of a lower average revenue AR_o' and average profit AZ_o', although both levels are capable of generating revenue TR_o, but with different total costs.

Since a lower level of fishing effort is associated with a lower fishing cost, the total cost associated with the harvest will be the lower one. Thus in terms of harvest, the restriction of fishing effort to E_o restricts the total harvesting cost to TC_o (figure 7.2(d)), average cost of harvesting a unit of fish to AC_o (figure 7.2(e)) and the average profit from harvesting a unit of fish to AZ_o (figure 7.2(f)).

The ability to restrict the average profit to a higher level and the average cost to a lower level seems to be the most favorable aspect of regulation associated with this scheme.

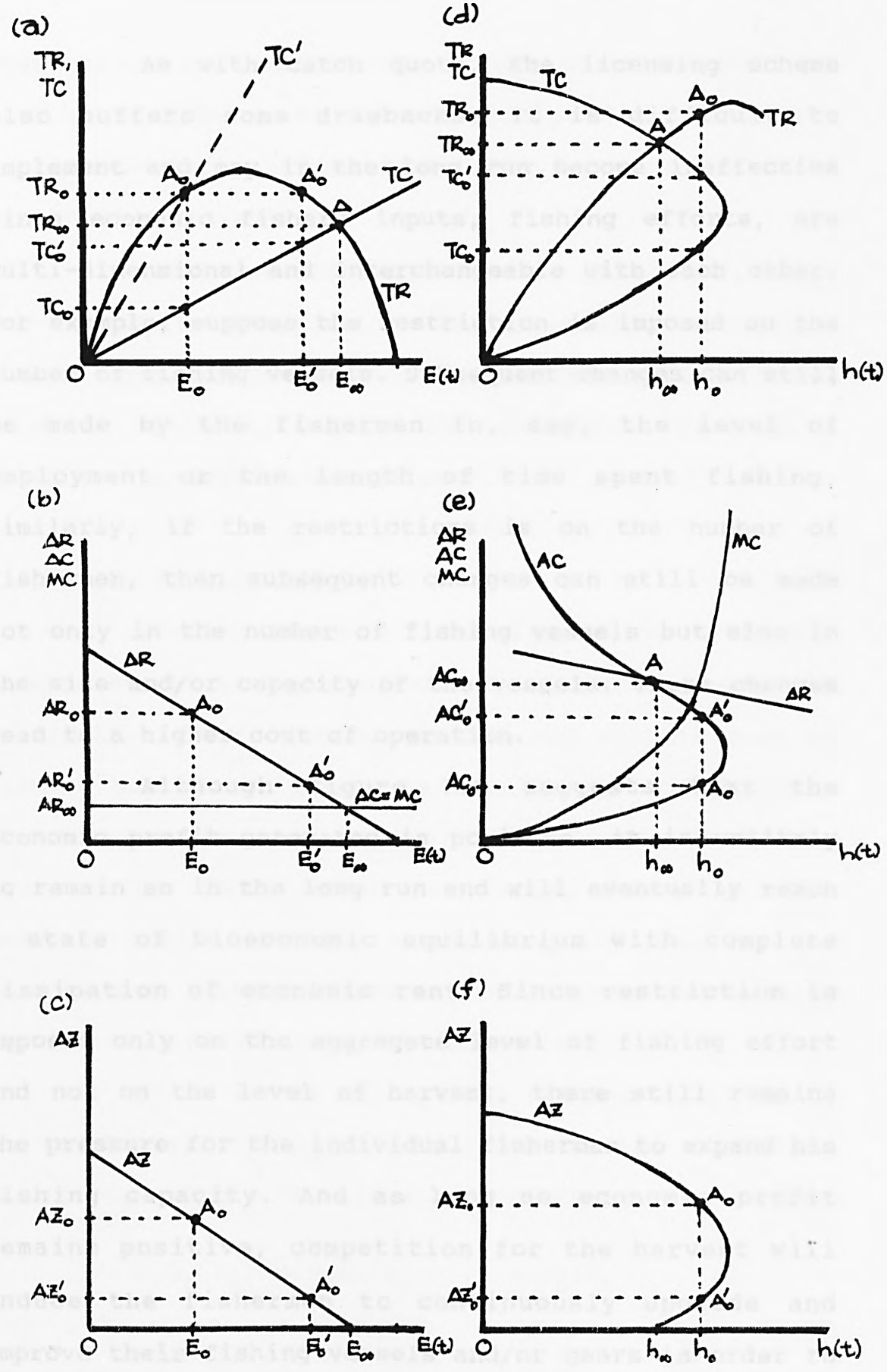


Figure 7.2 The licensing scheme

As with catch quota, the licensing scheme also suffers some drawbacks. It is difficult to implement and may in the long run become ineffective since economic fishery inputs, fishing efforts, are multi-dimensional and interchangeable with each other. For example, suppose the restriction is imposed on the number of fishing vessels. Subsequent changes can still be made by the fishermen in, say, the level of employment or the length of time spent fishing. Similarly, if the restrictions is on the number of fishermen, then subsequent changes can still be made not only in the number of fishing vessels but also in the size and/or capacity of the vessels. These changes lead to a higher cost of operation.

Although figure 7.2 suggests that the economic profit generated is positive, it is unlikely to remain so in the long run and will eventually reach a state of bioeconomic equilibrium with complete dissipation of economic rent. Since restriction is imposed only on the aggregate level of fishing effort and not on the level of harvest, there still remains the pressure for the individual fisherman to expand his fishing capacity. And as long as economic profit remains positive, competition for the harvest will induce the fishermen to continuously upgrade and improve their fishing vessels and/or gears in order to maintain or increase their shares of the harvest, thereby increasing the costs until a new bioeconomic

equilibrium is established at A_o with the economic rent from fishing being completely dissipated. The total cost curve shifts from TC to a higher level TC' (figure 7.2(a)).

Thus, in addition to being quite inflexible and difficult to implement, the licensing scheme also in the long run results in inefficient allocation of economic resources despite its ability to generate a short run positive economic rent.

7.4 Tax On Fishing Effort

Another form of regulation to maintain fishing effort at the desirable level is to impose tax on fishing effort, thereby raising the private cost of fishing beyond the actual harvesting cost of fishing. This results in a creation of a private bioeconomic equilibrium, that is an artificial state of zero economic profit, thereby eliminating any pressure for expansion of fishing effort and effectively maintaining the fishing effort at the desirable level.

If we denote the optimal fishing effort by E_o and the harvest by h_o (figure 7.3), the tax on fishing effort t_E should therefore be such that

$$Z(E_o,h_o) = p(h_o)h_o - (c + t_E)E_o$$
$$= 0 \quad , \qquad (7.1)$$

where $Z(E_o,h_o)$ is the profit, $p(h_o)$ is the unit price of the harvest h_o and c is the unit cost of fishing

effort. Expressing revenue TR in terms of fishing effort, equation (7.1) then gives

$$Z(E_o,h_o) = TR(E_o) - (c + t_E)E_o$$
$$= 0 , \qquad (7.2)$$

that is,

private profit from fishing
= private revenue - (private harvesting cost + tax paid on fishing effort)
= private revenue - private 'apparent' cost of harvesting
= 0 .

In figure 7.3(a), the tax on fishing effort raises the 'private' cost of fishing from TC to TC_o which reduces the level of fishing effort from E_{oo} to E_o, shifting the bioeconomic equilibrium from A to A_o. The 'private' average cost shifts vertically upwards from AC to AC_o (figure 7.3(b)) while the 'private' average profit decreases from AZ to AZ_o (figure 7.3(c)).

In terms of the harvest, the effect is reflected by the proportional rise in the total cost curve from TC to TC_o (figure 7.3(d)) which shifts the bioeconomic equilibrium from A to A_o. The average cost curve AC shifts vertically upwards by a constant amount A_oA_o' at every level of harvest to the new average cost curve AC_o (figure 7.3(e)). In figure 7.3(f), the average profit AZ is vertically depressed

by an equal amount at each level of harvest to a new average profit AZ_o so that the new private bioeconomic equilibrium is established at a harvest level h_o.

The economic rent from fishing which now takes the form of tax revenue is reflected by R_oC_o in figures 7.3(a) and 7.3(d), the product of A'_oA_o and OE_o in figure 7.3(b), the product of $E_oA'_o$ and OE_o in figure 7.3(c), the product of A'_oA_o and Oh_o in figure 7.3(e), and the product of $h_oA'_o$ and Oh_o in figure 7.3(f).

Since fishing effort is multi-dimensional and imposition of tax on every different combination of multiple factors of fishery production seems unpractical, the scheme then also suffers similar drawbacks as those encountered by the licensing scheme. For example, tax based on the number of fishing vessels will discourage the future purchase of fishing vessels. But more fishermen will be employed and the fishing vessels will be more extensively used than before, and eventually resulting in the increase in the cost of harvesting.

At the same time, it can also produce a distorting effect on the technology adopted. Following the tax on fishing vessels, the owners will be encouraged to reduce the number of fishing vessels and increase the catching power of the remaining vessels by increasing the size or equipment or the number of fishermen per vessel.

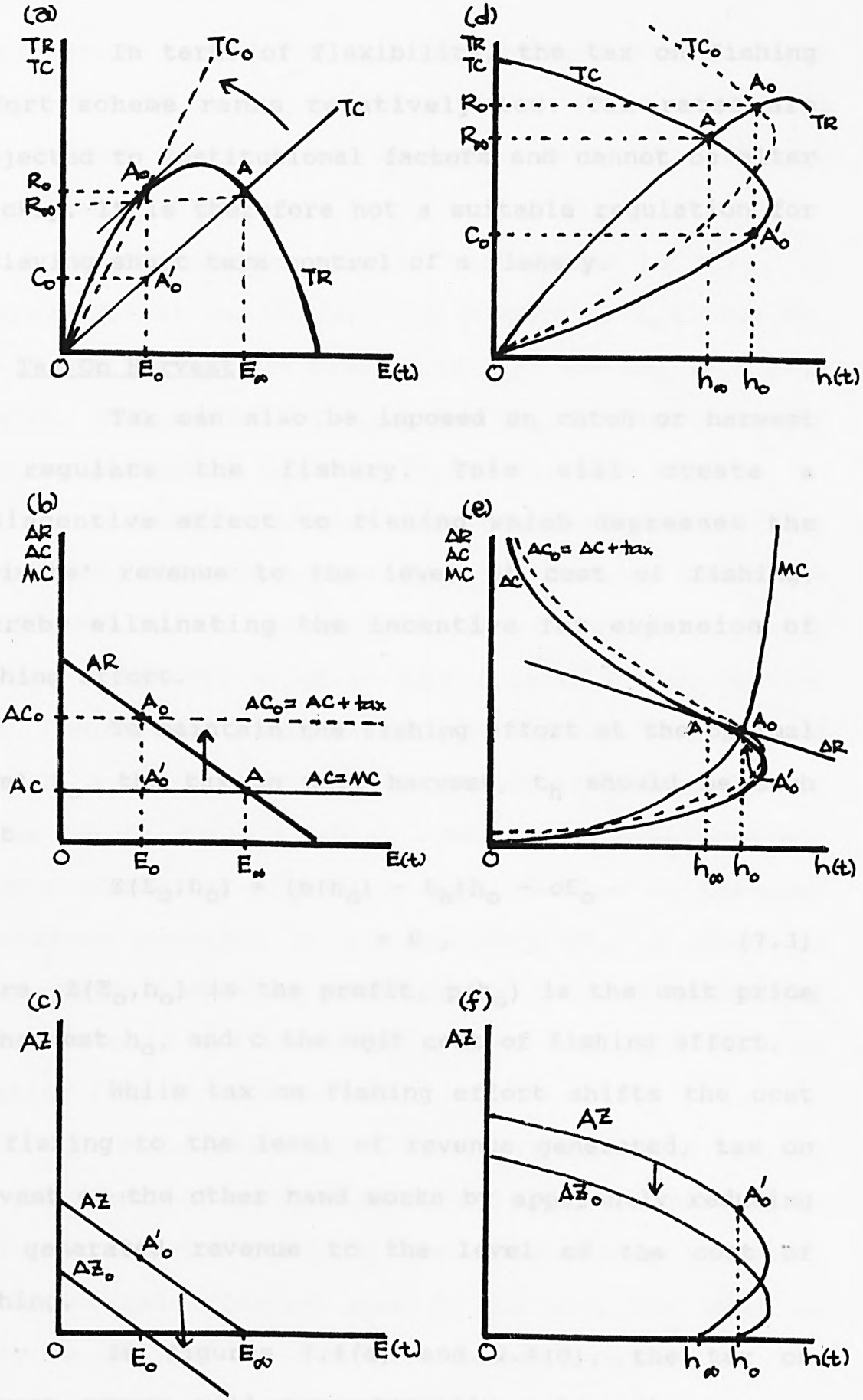


Figure 7.3 Tax on fishing effort

In terms of flexibility, the tax on fishing effort scheme ranks relatively low. Tax rates are subjected to institutional factors and cannot be alter quickly. It is therefore not a suitable regulation for achieving short term control of a fishery.

7.5 Tax On Harvest

Tax can also be imposed on catch or harvest to regulate the fishery. This will create a disincentive effect to fishing which depresses the 'private' revenue to the level of cost of fishing, thereby eliminating the incentive for expansion of fishing effort.

To maintain the fishing effort at the optimal level E_o, the tax on unit harvest, t_h should be such that

$$Z(E_o,h_o) = (p(h_o) - t_h)h_o - cE_o$$
$$= 0 , \qquad (7.3)$$

where $Z(E_o,h_o)$ is the profit, $p(h_o)$ is the unit price of harvest h_o, and c the unit cost of fishing effort.

While tax on fishing effort shifts the cost of fishing to the level of revenue generated, tax on harvest on the other hand works by apparently reducing the generated revenue to the level of the cost of fishing.

In figures 7.4(a) and 7.4(d), the tax on harvest scheme will proportionally reduce the revenue curves TR to TR_o, thereby shifting the bioeconomic

equilibrium from A to A_o. The average revenue curve drops from AR to AR_o (figures 7.4(b) and 7.4(e)), and the average profit curves drop from AZ to AZ_o (figures 7.4(c) and 7.4(f)).

The tax revenue is represented by R_oR_{oo} in figures 7.4(a) and 7.4(d), the product of A_oA' and OE_o in figure 7.4(b), the product of E_oA' and OE_o in figure 7.4(c), the product of A_oA' and Oh_o in figure 7.4(e) and the product of h_oA' and Oh_o in figure 7.4(f).

Whenever fishing effort exceeds the optimal level, say between E_o and E_{oo}, the fishery which was profitable before the introduction of tax now generates a negative profit which in turn creates a disincentive for fishing. Alternatively, any fishing effort less than E_o would motivate the expansion of fishing effort since it is capable of generating positive economic profit even after payment of tax. The tax on harvest, therefore provides an economically stable means of controlling fishing by artificially creating a state of zero economic profit which induces any diversion of fishing from it back to it.

While the multi-dimensional nature of fishing effort makes tax on fishing effort seems ineffective in the long run, the tax on harvest scheme seems to remain directive and effective even in the long run. This is largely due to the mono-dimensional nature of the harvest which eliminates the problem of defining tax on harvest.

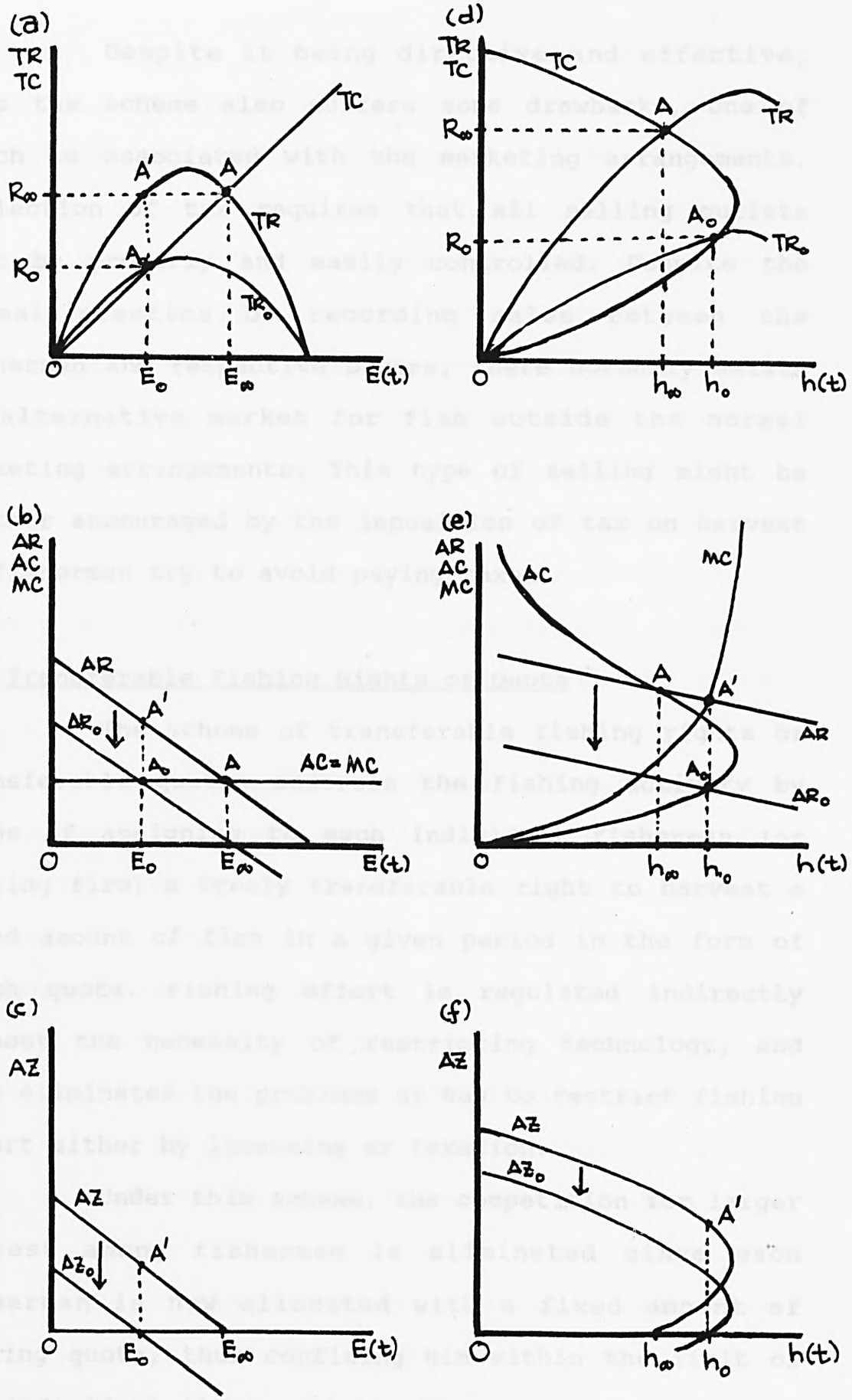


Figure 7.4 Tax on harvest

Despite it being directive and effective, this tax scheme also suffers some drawbacks, one of which is associated with the marketing arrangements. Collection of tax requires that all selling outlets must be properly and easily controlled. Despite the normal practice of recording sales between the fishermen and respective buyers, there normally exists an alternative market for fish outside the normal marketing arrangements. This type of selling might be further encouraged by the imposition of tax on harvest as fishermen try to avoid paying taxes.

7.6 Transferable Fishing Rights or Quota

The scheme of transferable fishing rights or transferable quotas controls the fishing activity by means of assigning to each individual fisherman (or fishing firm) a freely transferable right to harvest a fixed amount of fish in a given period in the form of catch quota. Fishing effort is regulated indirectly without the necessity of restricting technology, and this eliminates the problems of how to restrict fishing effort either by licensing or taxation.

Under this scheme, the competition for larger harvest among fishermen is eliminated since each fisherman is now allocated with a fixed amount of fishing quota, thus confining him within the limit of his individual fishing right. Although the competition leading to dissipation of economic rent is avoided, a

different form of competition may still exist between fishermen, especially if some fishing grounds are more productive than others. Fishermen will be induced to rush into harvesting as they attempt to achieve their fishing quotas early in the season since reduction in the available fish stock by other fishermen's harvesting means an increase in their unit cost of harvesting. This in turn might create an incentive for the fishermen to acquire more efficient vessels. However, since the individual quota does guarantee the fishermen their fishing rights, the upgrading of vessels is unlikely to be as great as in a system of either aggregate catch quota or licensing of fishing effort.

This scheme of transferable fishing rights is also capable of creating a market of fishing rights. Since the fishing rights are transferable, fishermen now have the options of either to use or to sell their fishing rights to those who are willing to pay the highest price for the fishing rights. This market for individual fishing rights will eventually result in the reallocation of resources in fishery with the fishery being carried out by the minimum-cost fishermen.

Consider a fishery which is being exploited by a single fishing effort E whose unit cost varies among fishermen. Let the minimum unit cost of fishing effort be c_{min}, and the combination of harvest and fishing effort that satisfies the optimum condition be

h_o and E_o respectively. Further, assume that the total optimal aggregate harvest h_o is allocated in small even quotas among the fishermen.

Thus the fishermen equipped with minimum-cost technology will expect to generate an average profit (for a unit of harvest) of

$$AZ_2 = \{p(h_o)h_o - c_{min}E_o\}/h_o \tag{7.4}$$

where $p(h_o)$ is the unit price of the harvest.

Similarly, other fishermen without the minimum-cost technology would generate an average profit (for a unit cost of harvest) of

$$AZ_1 = \{p(h_o)h_o - cE_o\}/h_o \tag{7.5}$$

where c ($> c_{min}$) is the unit cost of fishing effort. Since $c_{min} < c$, we then have

$$AZ_2 > AZ_1 \ . \tag{7.6}$$

This difference in average profit gives rise to the creation of market for fishing rights. Any fisherman with a fishing right and an expected average profit of AZ_1 would be a potential supplier of fishing rights if the price of fishing rights is higher than AZ_1. And the demand for fishing rights will come from those fishermen with minimum unit cost of fishing effort since they earn the highest average profit AZ_2.

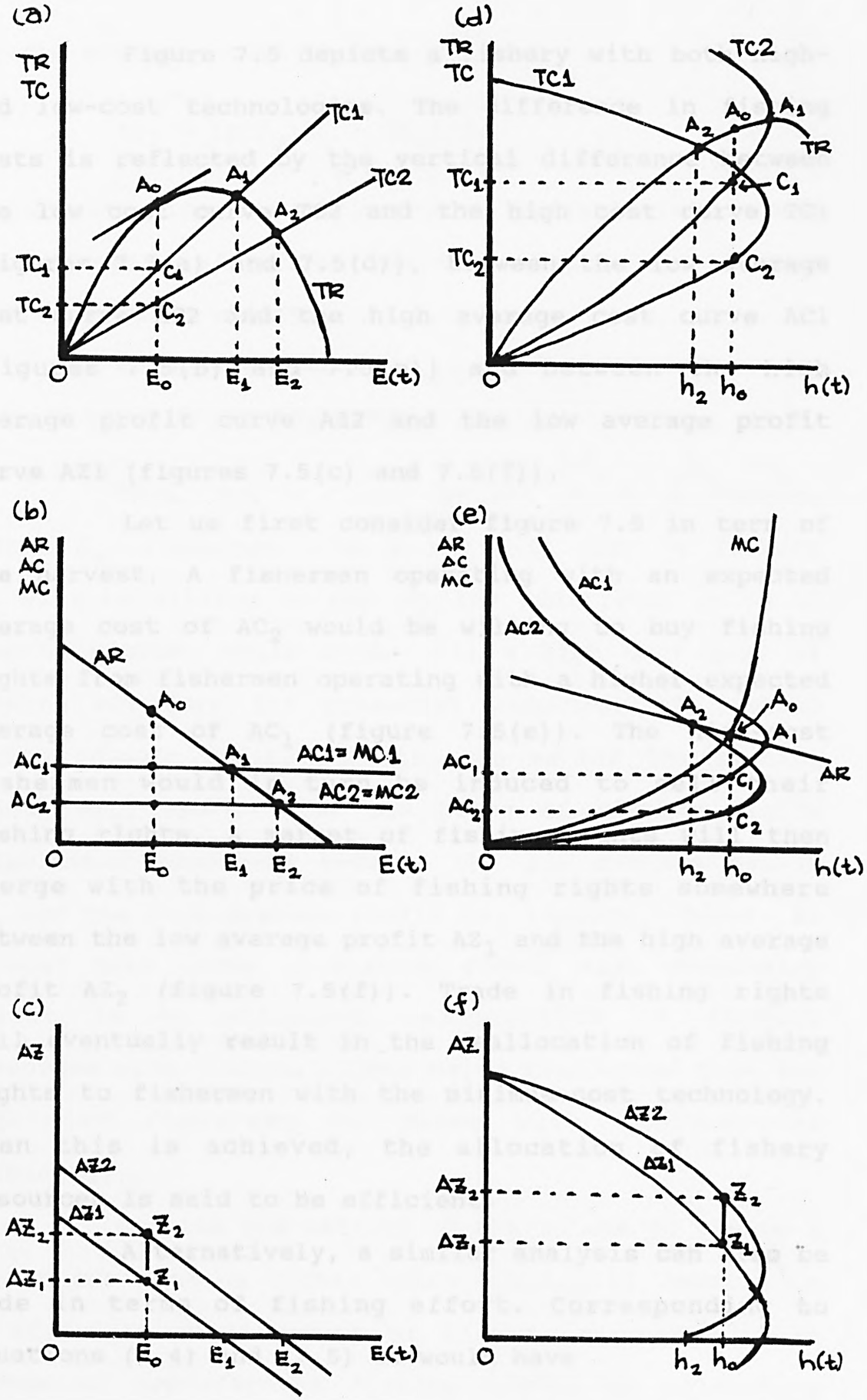


Figure 7.5 Transferable fishing rights

Figure 7.5 depicts a fishery with both high- and low-cost technologies. The difference in fishing costs is reflected by the vertical difference between the low cost curve TC2 and the high cost curve TC1 (figures 7.5(a) and 7.5(d)), between the low average cost curve AC2 and the high average cost curve AC1 (figures 7.5(b) and 7.5(e)) and between the high average profit curve AZ2 and the low average profit curve AZ1 (figures 7.5(c) and 7.5(f)).

Let us first consider figure 7.5 in term of the harvest. A fisherman operating with an expected average cost of AC_2 would be willing to buy fishing rights from fishermen operating with a higher expected average cost of AC_1 (figure 7.5(e)). The high-cost fishermen would in turn be induced to sell their fishing rights. A market of fishing rights will then emerge with the price of fishing rights somewhere between the low average profit AZ_1 and the high average profit AZ_2 (figure 7.5(f)). Trade in fishing rights will eventually result in the reallocation of fishing rights to fishermen with the minimum-cost technology. When this is achieved, the allocation of fishery resources is said to be efficient.

Alternatively, a similar analysis can also be made in terms of fishing effort. Corresponding to equations (7.4) and (7.5) we would have

$$AZ_2 = \{p(h_o)h_o - c_{min}E_o\}/E_o \qquad (7.7)$$

for the minimum- cost technology, and

$$AZ_1 = \{p(h_o)h_o - cE_o\}/E_o \qquad (7.8)$$

for others with non-minimum-cost technologies, where the average profits are now expressed as profit per unit of fishing effort.

As before, since $c_{min} < c$, we then have

$$AZ_2 > AZ_1 \ . \qquad (7.9)$$

Thus, for a given optimal level of fishing effort E_o, fishermen with a low unit cost of fishing AC_2 will be willing to pay for the additional units of fishing rights, while those with a high unit cost of fishing AC_1 form the potential suppliers of fishing rights (figure 7.5(b)). Again, the market for fishing rights will emerge with the price of fishing rights established somewhere between the low average profit AZ_1 and the high average profit AZ_2 (figure 7.5(c)). As before, this trade in fishing rights will eventually result in an efficient reallocation of fishery resources with fishing rights being tranferred from the high-cost fishermen to those with minimum-cost technology.

Despite the ability of the scheme to create a market for fishing rights which eventually results in an efficient reallocation of fishery resources, this system of transferable fishing rights by allocating transferable fishing quotas without restriction on

fishing effort can in some circumtances lead to instability in the population (Waugh, 1984).

Consider figure 7.6 where the total aggregate transferable quota is set at h_o. This quota is consistent with an equilibrium population level of either B_1 or B_2. The higher population level B_2 is a position of stable equilibrium. Any deviation will force the population back to the equilibrium since if the population falls (rises) the natural growth rate exceeds (falls below) the harvest quota, thereby driving it back to the equilibrium level B_2. Population level B_1 is however semi-stable. Small perturbations in its level need not automatically forced the population back to B_1.

Thus it seems that quotas are not an effective tool in controlling the population if it is at a low level, for example, level below B_1. A better alternative will be to control the level of fishing effort E_1. Even then, there is no certainty that the population will not deplete if it is already at a very low level. Harvesting should then be restricted further (either by licensing the fishing effort or a lower quota on harvest or both or a complete ban on fishing) until the population recovers to some sustainable level. When that is achieved, the control can then be by means of tranferable fishing rights.

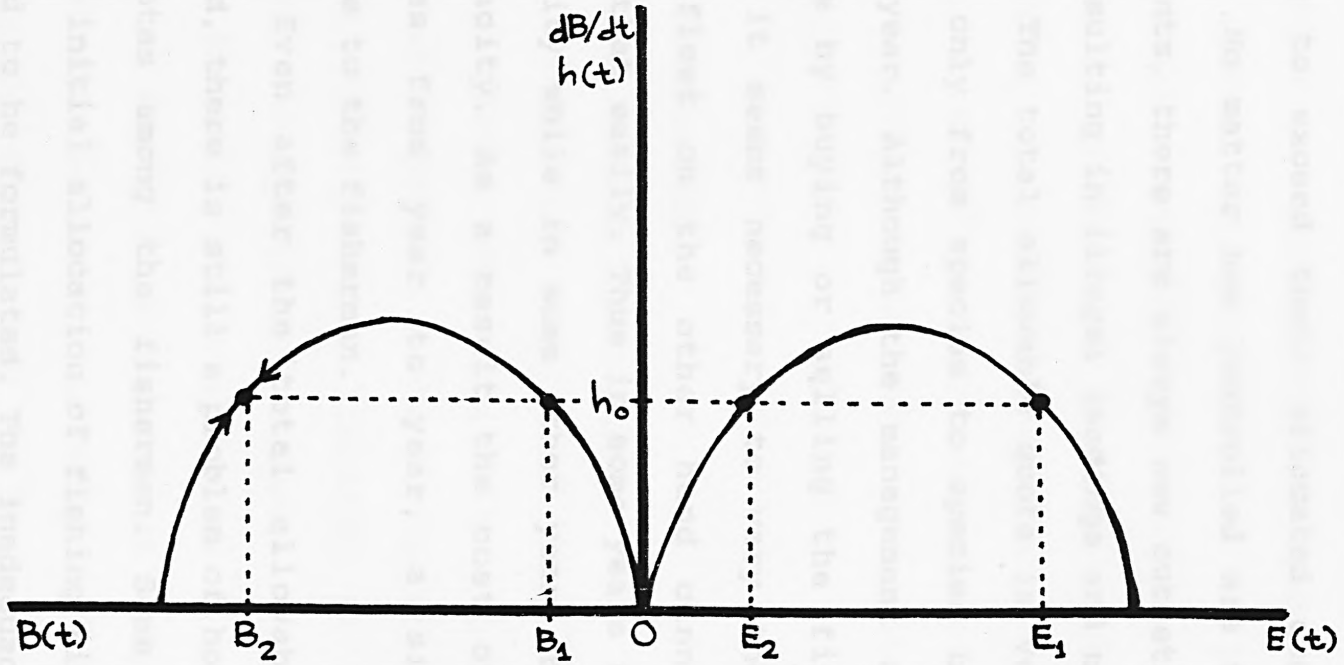


Figure 7.6 Transferable fishing rights and control of population

As with other management schemes, the system of transferable fishing rights also encounters problems with its implementation and enforcement. The emergence of significant economic rent is likely to induce fishermen to exceed their allocated quotas whenever possible. No matter how controlled are the marketing arrangements, there are always new outlets for illegal catch, resulting in illegal landings and marketings.

The total allowable quota is very likely to vary not only from species to species but also from year to year. Although the management authority can intervene by buying or selling the fishing rights whenever it seems necessary to vary the quota, the fishing fleet on the other hand cannot vary its capacity that easily. Thus in some years there will be overcapacity while in some other years there will be undercapacity. As a result the cost of harvesting fluctuates from year to year, a situation not favourable to the fishermen.

Even after the total allowable quota is determined, there is still a problem of how to allocate these quotas among the fishermen. Some criteria on which the initial allocation of fishing rights is to be based need to be formulated. The inadequacy or in some cases the unavailability of reliable data only makes the problem more difficult.

Thus the scheme of transferable fishing rights can play a useful role in fisheries management

when there is a need for a flexible scheme of control (since it is easy to vary quotas) provided that the marketing arrangements are such that enforcement is not difficult. Despite its ability to indirectly restrict fishing effort and prevent the dissipation of economic rent, its success depends largely on the success of its implementation and enforcement. In cases where enforcement of transferable quota is costly, or likely to be met by uncertain or unlikely acceptance by fishermen, or where stricter controls over population stock are required, other forms of regulations may be preferable.

7.7 Other Regulations

7.7.1 Restrictions on fishing gear

Perhaps one the least desirable ways of controlling fishing effort and which has been the most controversial subject in fishery regulation is the one which limits the freedom of fishermen to adopt certain fishing gear and technology. Although such a regulation is easy to implement and is effective in preventing the depletion of the fish stock, it is very inflexible. Once a certain technology is adopted it is normally embodied in the fishery for the economic life of the equipment and any regulation that tends to restrict its operation or calls for its adjustments before it can be put into operation is going to add to the cost of harvesting to the fishermen. Such action normally

results in the technology adopted being economically less efficient.

Basically, there are two objectives in restricting fishing gears. Firstly, it is to save the fish stock from complete destruction, and secondly to provide a sufficiently large increase in the value of future harvests by ensuring that only fish of optimal age are caught. The concept of optimal age or size of first capture is closely related to the concept of eumetric fishing (Beverton and Holt, 1957) where it is assumed that the size of fish caught can be equated to some combination and/or size of the fishing gear. Thus increasing the mesh size, for example, will allow the young fish to escape and grow so that it can be harvested at a later time when it reaches an optimal size. Without regulation restricting mesh size fishermen competing for the harvest will use the smallest mesh size that harvests marketable fish, for if they leave the small fish to grow it would probably be caught by other fishermen.

The mesh size regulation also has its limitations. It works fairly well in trawl fisheries but only over a range of sizes. A mesh, in general does not produce a 'knife-edge' selectivity (Clark, 1976), and a given mesh size will normally take a few small fish with a greater proportion of larger fish.

Furthermore, most fishing vessels harvest more than one species at a time and the optimum size of

each species will almost certainly differ from one another. A mesh large enough to allow one species to escape and grow may leave all other species of smaller optimal size unharvested. Reducing the mesh size to allow harvest of the second species might reduce or even destroy the stock of the first species.

From the fishermen's point of view, mesh size regulation also increases their cost of fishing (at least in the short run) since changing the existing mesh size to comply with the regulation can be expensive.

Although regulating the size of fish caught is generally popular with biologists since it is capable of saving the stocks from depletion, it is less acceptable by economists. Its only economic justification lies in the possibility of it generating a larger future value of harvest. Those fish allowed to escape harvesting must be susceptible to the gear at a later time with a fairly high probability of being caught. At the same time, the growth rate must be large relative to the natural mortality rate so that the expected increase in future value of the harvest is sufficient to compensate for the extra time loss in waiting for the fish to reach its optimum size. The effect on cost of harvesting must also not be ignored. As fish are allowed to grow to its optimum size, they become more distributed over a larger area and harvesting may become more expensive.

Thus although mesh size regulation is capable of saving a depleting stock as well as of ensuring a better future harvest, it must also be weighed against the economic aspects of costs and benefits as stressed by Boyd (1966),

> "...Only if the decreased costs associated with the increased steady-state fish stock at least offset the increased production costs due to the larger mesh size , however, will a larger mesh size be Pareto-superior. If, and only if, this is indeed the case will external diseconomies due to larger fish available in the future exist, and then, and only then, will some sort of regulation of mesh be necessary for Pareto-optimum..."

(Boyd, 1966, American Economic Review, 56:511-517)

It should also be stressed that the regulation of mesh size requires the knowledge of the optimum size of catch either in terms of individual weight or age. And this is not easy to determine in most commercial fisheries since the harvests are normally recorded in term of the aggregate biomass and not in term of individual size. Thus its application in a Schaefer or surplus production model is limited.

7.7.2 Closed seasons

The regulation of closed seasons operates by limiting the fishing time in any one year. It is equivalent to the catch quota system. The opening of the season is determined in advance together with the total allowable catch for the season. Once this quota is reached the season is closed until the following

year.

Such regulation is simple, direct and easy to implement. It requires no complex decision as to who is to fish and how should the fishing effort and harvest be distributed between the fishermen. The market is allowed to operate freely during the season with the most efficient operators taking most of the harvest. And whenever necessary, closure of the season can be immediate, for example if the stock is expectedly threatened.

Similar drawbacks associated with the catch quota system also apply. The fishing season will be shorter as fishermen rush to harvest. This results in 'peak load' period which will add strains on the processing plants. Since entry to the fishery is not subjected to any restriction, the fishery will eventually be driven to the state of open-access bioeconomic equilibrium with a complete dissipation of economic rent.

Thus a closed season by itself is unlikely to result in optimal management of the fishery. However, it can form a vital back-up measure as a short-term regulation "if and when things do not work as planned" (Cunningham et al, 1985).

7.7.3 Closed areas

Under certain circumtances some areas of the sea are closed to fishing for all or part of the season. This is generally introduced to protect either the young or the spawning fish in the nursery areas with the hope of increasing the value of the future harvests. In some cases, it is introduced in order to protect the immature fish of one species which are being harvested as a by-catch of a fishery directed at a different species, for example, the introduction of the Norway pout box in the North Sea where immature haddock and whiting are protected from the industrial fishery directed at Norway pout (Cunningham et al, 1985).

However, from the economic point of view, the spawning period is probably the best time to fish. The congregation of fish stocks during spawning makes them particularly easy to harvest, thereby lowering the cost of harvesting. Furthermore, the fish themselves are in their best conditions.

Thus the closure of fishing areas can only be economically justified if the expected future gains exceed the losses incurred as a result of the closure. These losses include the extra costs in fishing a more dispersed population, the interest costs in waiting for the chance of future harvests and the extra costs of enforcement. Finally, it can also lead to a state of open-access bioeconomic equilibrium, another case of

misallocation of resources.

7.8 Fishery Management At National Level (The Case of United Kingdom)

The need to regulate fisheries within its national water has become more apparent in United Kingdom (UK) in the last two decades or so. The broad objectives have been both economic as well as biological. The economic objective has been concerned mainly with improving and promoting its domestic fishing industry through research and development as well as financial aids such as operating subsidies to the fishing sector. On the biological side, the aim is to regulate fishery within its water so as to maintain a balance between the level of fishing activity and the need for conservation of stocks. Various biological controls have been enforced during the years. These include closed areas, closed seasons, minimum mesh sizes and minimum landing sizes of fish, gear controls, catch quotas as well as licensing and temporary ban on the harvesting of some species in certain areas.

The financial aid have been given by the government since 1950. Total aid given by the British government to the catching sector of industry over the period 1978-81 has amounted to £89 million (Cunningham et al, 1985), not including those received from the European Economic Community (EEC). In addition, individual projects in UK also received financial aids

from Fonds Europeen d'Orientation et Garantie Agricole (FEOGA).

The financial support given by the government during the past years has probably help marginal fishing firms and vessels to continue to be in operation. The introduction of White Fish Authority Grant and Loan Scheme for the construction of vessels less than 140 feet (43 metres) in length has resulted in the growth of such vessels in Wales and England from 29 six years before the scheme to 117 six years after the scheme. Research and development has also produced positive effects in areas such as marine fish farming, stock assessment as well as gear technology and fishing methods.

Although the fisheries regulations within the European water became the responsibility of EEC from 1977, a number of measures dealing with specific conservation problems were initiated and enforced by the British government. This is partly due to the absence of an agreed Common Fishery Policy (CFP) within EEC — the CFP was finally agreed only in early 1983, after six years of negotiation.

In response to falling catches of herring, a temporary ban on herring fishing in the North Sea was initiated in 1977. Less severe regulations were also imposed for cod, haddock, whiting and mackerel in later years. In 1978 the fishing of Norway pout in area West of Shetlands was banned and a year later a similar ban

was imposed on herring fishing in areas in the North Sea, west of Scotland and Mourne, and a fishing quota of 2000 metric tons was introduced for herring fishing around the Isle of Man. These conservation measures imposed by the British government were declared illegal by the European Court in July 1980. In mid-August 1980, the government announced a ban on fishing for mackerel in the North Sea.

In addition to the above conservation measures, a licensing scheme was also adopted by the government. Before 1983 the aim of the licensing was not to restrict entry (except for a few cases) but rather to monitor the amount of fishing effort to help in the allocating and enforcing of quotas. In 1982 the licensing scheme was extended to include transhipping of main pelagic species from UK vessels within UK fishery limits to any other vessels, domestic or foreign.

A system of licensing scheme was introduced in September 1977 to control mackerel fishing by UK vessels and continued to be operative into 1980's. In early 1980's a more restrictive licensing covering several species was made. This includes mackerel, cod, herring, haddock and whiting. Herring fishery was reopened in 1981 in areas West of Scotland, southern North Sea and East English Channel, and West English Channel subject to total quotas and licensing for UK vessels. The fishing of herring in North Irish Sea by

UK and Isle of Man vessels continued to be regulated by licensing scheme while herring fishing elsewhere was banned. The fishing of cod, haddock and whiting in the North Sea and West of Scotland in late 1970's and early 1980's were also subjected to licensing, but only haddock was subjected to quantitative controls which were lifted on 27 September 1981 (OECD, 1982).

With the agreement of a CFP within the EEC in early 1983, a system of total quotas were set for several species and allocated to Member States. Following this, some of "the stocks for which UK quotas were considered insufficient to allow unrestricted fishery" were designated as 'pressure stocks' (OECD, 1985), and a system of restrictive licensing was introduced. From 3 February 1984, licenses for any 'pressure stock' will not be granted to UK vessel of over 10 metres unless it has a recent record of fishing such 'pressure stocks'. In 1985, Western hake was included in the 'pressure stocks' and a similar licensing policy was imposed on it.

In terms of fishing vessels, the licensing controls were extended in 1984 from vessels of 40 feet or more to vessels of at least 10 metres, in accordance with the EC's Control Regulation. A year later, new licensing measures were announced and became effective on 1st January 1986. Under this new scheme, "all registered UK vessels must now meet criteria concerning crew nationality and regular landings in or calls to

UK ports, to qualify for a license" (OECD, 1986). This is to protect UK quotas from being taken up by vessels with little or no economic link with UK and to ensure that these quotas are used to benefit the UK fishing industry.

Perhaps one of the events that produces great impact on the fishing industry in UK (and her EEC partners) is the extension of UK fisheries limit to 200 miles Exclusive Economic Zone (EEZ) in January 1977. The immediate effect was the eviction of most of the non-EEC vessels especially from the Eastern-bloc which formed the major fishing fleet in Western areas in early 1970's. This opportunity was quickly taken up by UK vessels with a result of large increase in landings, notably that of mackerel. In fact by 1979, mackerel constituted to over 40 percent of the total weight of all fish landed in UK by domestic vessels and this amounted to roughly what the Eastern-bloc had been taking four years previously. Non-EEC countries which had reciprocal arrangements and were granted access to EEC waters include Norway and Faroe Island and later Sweden (in 1984).

The extension of 200-mile fishing limit also has negative effects on the domestic fishing industry. Following similar adoption by other countries, UK fishing vessels now loss access to traditional distant-water areas except where reciprocal arrangements had been made. Some of the species, for example cod, were

less abundant in the UK waters. At the same time, with its accession to EEC, fishing vessels of other EEC countries now have free access to UK Exclusive Economic Zone, creating more competition for the fish resources.

Despite the various regulating measures adopted by the British government, the conservation of some stocks does not appear to be successful. In most cases, restrictions were imposed after overfishing had occured, for example the banning of the North Sea herring fishery in 1977. At the same time, the British government has limited control over non-British EEC fishing fleet. Thus it seems that more effective control can be achieved by regulations taken at a higher level, the EEC.

7.9 Fishery Management At International Level (The Case of EEC)

A number of international fishery organisations had been founded since early this century. The International Council for the Exploration of the Sea (ICES) was established in 1902 to provide a forum for the exchange of scientific ideas between biologists. It has since increased in importance and been actively engaged in a number of scientific researches and is also one of the main advisory bodies on the management of international fisheries. The end of second world war saw the emergence of the North East Atlantic Fisheries Commission (NEAFC) and the International Commision for

Northwest Atlantic Fisheries (ICNAF) in 1950 which was replaced by the Northwest Atlantic Fisheries Organisation (NAFO) in 1979. Other specific international bodies include the International Whaling Commission (IWC), founded in 1946 for the international management of whales, International Commission for the Conservation of Atlantic Tuna (ICCAT), established in 1969 for the tuna management in the Atlantic, as well as the Inter American Tropical Tuna Commission (IATTC), established in 1949 following an agreement between the United States of America and the Costa Rica concerning tuna fishing in the eastern Pacific.

Despite the continuous recommendations made by these organisations to the need for fishery regulations, most of it were either ignored or enforced only when the situation has become critical. This is largely due to the refusal or late acceptance by the countries concerned. Take the North Sea herring fishery for example. Following the near collapse of the East Anglia herring fishery in 1960's a study group was set up by NEAFC to look at managing its stock. A total allowable catch scheme was recommended but was only accepted by the member countries in 1974 without an exact agreement on what the total quota should be. In 1974 to 1976 the agreed total quota was greater than that recommended, and even then it was not enforced because of the objections by some member countries (the quota needed a two-third majority before it can be implemented). In

November 1975, ICES strongly argued that herring fishery in the North Sea should cease, yet a total quota of 160000 metric tons for 1976 was agreed but not enforced with the actual catch reaching 183000 metric tons. Only in April 1977 were the member countries finally persuaded to accept and enforce a total ban on herring fishing in the North Sea. Its management by then had become the responsibility of the EEC following the extension of the 200-mile EEZ on 1 January 1977.

The adoption of the 200-mile limit reduces the role played by the international fishery organisations in regulating international fisheries. However, ICES will continue to provide advice on the biological basis while the jurisdictions of the NEAFC and NAFO will be restricted to areas beyond the national 200-mile limits. The coastal states (including the EEC) are free to accept or reject any recommendation or advice given by these bodies.

Instead of placing the control of fisheries under each individual country, the adoption of the 200-mile EEZ by the coastal member states of the EEC brings the control and management of fisheries within the EEC waters under a cooperative group comprising of the member states of the EEC. A Common Fishery Policy (CFP) was originally agreed by the first six members of the EEC (Belgium, France, West Germany, Italy, Luxembourg and Netherlands) without much opposition since none of the members then had particularly important inshore

fisheries. However, the accession of United Kingdom, Eire and Denmark to EEC on 1 January 1973 (at the same time Norway opted not to join the EEC due to the unfavourable CFP) made it necessary to renegotiate the CFP since these new members all have important fisheries and fishing grounds that are of considerable interests to other member countries. This resulted in a ten-year transitional period lasting until 31 December 1983. During this period no significant alterations was to be made on CFP and a coastal belt of six to twelve miles was to be reserved for local fishermen subject to the historic fishing rights of EEC fishermen. The general objectives of the CFP at that time include 'the rational use of the biological resources of the sea, the prevention of overfishing, and the prevention or reduction of over-capitalization'. These are to be achieved by the use of 'the necessary conservation measures' which include restriction on harvesting of certain species, restricting access to certain areas, controls on fishing seasons, methods of fishing and types of fishing gears used.

After years of negotiations, the EEC finally agreed to adopt a system of total allowable catches (TAC's) or total quotas. These TAC's are to be divided into national quotas and allocated between the member countries. However, the absence of mutually agreeable criteria to base the allocation of quotas prolonged its implementation. UK (with a fishing zone that accounted

for about 60% of the total EEC catch) for example, argued that quotas should be linked to the contribution made by each country to the total EEC resource base. At the same time losses suffered from being excluded from distant-water fishing grounds following the extension of 200-mile EEZ by non-EEC countries should also be taken into account. The continental members of EEC (with smaller contribution to the fish base) however argued that quotas should be based mainly on the historic performance of the fishing fleets.

On 25 January 1983, the EEC Council eventually adopted the new CFP with the allocation of national quotas among the member countries being based on historic fishing performance with some consideration on regional dependence on fishing and distant-water losses. These quotas are set on year to year basis following recommedation and advice on the stocks of different species by ICES. Table 7.1 summarises these share-out quotas for 1983-1985 among the member states. It was also agreed that the six-to-twelve mile coastal belt will continue to be enforced until 31 December 1992, when it will then be standardised to twelve miles in all places. Other regulatory measures were also adopted by the Council. These include the 'adoption of fishing log book by vessels of Member Countries and the establishment of an inspection and supervision unit in the maritime waters and fishing ports of the Community'

SPECIES	BELGIUM	DENMARK	FRANCE	GERMANY
COD	9330	183380	39820	69310
	(8230)	(236350)	(36950)	(84380)
	(9150)	(239570)	(35280)	(87800)
HADDOCK	1960	21450	21130	8430
	(1670)	(18615)	(19340)	(7110)
	(1700)	(17880)	(19940)	(7120)
SAITHE	90	8390	74840	23230
	(80)	(7550)	(69850)	(21110)
	(80)	(6630)	(64340)	(18760)
WHITING	4090	35980	40190	4370
	(3680)	(34190)	(37510)	(3900)
	(4300)	(36880)	(41550)	(4600)
PLAICE	13325	51460	8020	10830
	(12085)	(46110)	(7345)	(9860)
	(11080)	(43730	(7340)	(8900)
SOLE	4035	1360	5730	1500
	(3825)	(1280)	(5365)	(1360)
	(3910)	(1280)	(5070)	(1360)
MACKEREL	330	8350	16330	24330
	(100)	(7400)	(17100)	(25600)
	(-)	(13500)	(16000)	(24000)
SPRAT	1400	139270	2700	4730
	(1100)	(110830)	(2400)	(3520)
	(100)	(24600)	(1400)	(900)
HERRING	9120	145980	37270	70770
	(7100)	(75050)	(22640)	(41900)
	(8300)	(51690)	(19440)	(26460)
HAKE	250	2340	21480	100
	(240)	(2150)	(21220)	(100)
	(250)	(2150)	(21800)	(100)

Note: 1. No quota was allocated to Greece, Italy and Luxembourg.

2. Figures in brackets refer to 1984, 1983 respectively.

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SPECIES	IRELAND	N'LANDS	U.K'DOM	TOTAL
COD	11520	26820	128240	468420
	(11520)	(23230)	(117910)	(518570)
	(11720)	(26250)	(131070)	(540840)
HADDOCK	4050	1340	159070	217430
	(4370)	(1120)	(140840)	(193065)
	(4730)	(1120)	(145410)	(197900)
SAITHE	3060	210	22480	132300
	(3060)	(190)	(20860)	(122700)
	(3060)	(170)	(19060)	(112100)
WHITING	17800	9670	86600	198700
	(17800)	(8630)	(79480)	(185190)
	(17800)	(10190)	(90200)	(205520)
PLAICE	3295	73620	59000	219550
	(3070)	(66890)	(53760)	(199120)
	(3070	(60420)	(49070)	(183610)
SOLE	555	16980	3025	33185
	(555)	(15475)	(2870)	(30730)
	(585)	(15490)	(2725)	(30420)
MACKEREL	80000	35330	220330	385000
	(85300)	(37300)	(234700)	(407500)
	(80000)	(35000)	(220000)	(388500)
SPRAT	-	3350	43000	194450
	(-)	(2900)	(41500)	(162250)
	(-)	(1400)	(10500)	(313900)
HERRING	32880	87720	105610	489350
	(31660)	(48970)	(75780)	(303100)
	(27960)	(30110)	(66120)	(230080)
HAKE	1300	200	4430	30100
	(1300)	(200)	(4390)	(29600)
	(1300)	(200)	(4500)	(30300)

Source: OECD (1985, 1986)

Table 7.1 Share-out quota system among EEC member countries (metric tons), 1983-1985

in June 1982 (OECD, 1983). On 1 April 1985, the adoption of log book for recording all daily catches of species subjected to TAC became compulsory for fishing vessels above 10 metres.

In addition to the share-out quota system, the new CFP also laid down five technical measures for the conservation and management of fish resources —— mesh size restriction, fish size restriction, closed areas, closed seasons and gear restictions —— which were actually similar to those spelled out by the former CFP.

Following the accession of Spain and Portugal to the EEC on 1 January 1986, the CFP, in particular the national quotas allocated between member countries needs to be revised. Whatever the outcomes of this revision, it is unlikely that it will benefit all member countries.

It seems that the CFP adopted by the EEC is too dependent on biological method, for example the adoption of TAC, with little control on fishing effort either directly or indirectly. Although the CFP also spelled out the various technical measures to be adopted, it is yet to be effectively implemented and enforced. At the same time, the fishery still remains one of open-access, at least to EEC countries. Although restrictions were imposed by some member countries, for example the strict licencing scheme by UK, it only applies to its own domestic fishing fleet with little

or no control over the fishing fleet of its EEC partners.

In December 1988, after 23 hours of talks in Brussels between Europe's North Sea fishing nations, the EEC ordered a cut of 65% in the British catch for 1989 which include a reduction of more than half on haddock catch, a reduction in mackerel and a freeze on cod quotas. These cuts in harvest is estimated to cost British fishing industry £40 million and thousands of jobs (The Sun, 12 Dec. 88). This reduction and freeze on some quotas are likely to continue into the future.

Thus it appears that a radical revision of the CFP to include a more direct controls over fishing activity such as restricted licensing or an indirect control such as transferable fishing rights within all member states of EEC is required if the full benefits are to be realised from the adoption of 200-mile EEZ.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary

In this study a model of the harvesting of interdependent self-renewable natural resource in a multispecies ecosystem was constructed. The major components of the model are biological submodel describing the dynamics of the resource, an economic submodel describing the economics and dynamics of the exploitation process, and a harvest (production) function bridging these two submodels.

The model developed is capable of describing the population dynamics of any finite number of self-renewable natural resources within a given environmental framework, as well as accommodating any finite number of economic inputs, for example the fishing effort. The complexity surrounding the Beverton-Holt type model for an exploited population precluded empirical use, so attention was directed on the homogeneous mass growth function. The commonly used logistic (or Schaefer's surplus production) function was adopted as an approximation to the general growth function, and an empirically useful version was constructed.

On the production side, a function capable of compressing any finite number of economic inputs into a single equivalent composite directed economic input was developed. The price (demand) and cost functions were

assumed to be linear in harvest and fishing effort respectively.

The model was formally extended to include fairly general biological interspecies relationships which were briefly analysed for three specific cases — predator-prey, competition and symbiotic. This led to the construction of a dynamic multispecies optimization model, the objective being the maximization of the total present value, that is the discounted total economic profit generated from the exploitation, subject to the population dynamics of the biological submodel. Due to the limitations of analytical techniques in solving a multi-dimensional problem, the final multispecies model was reduced to an empirical form. This was to facilitate in the estimation of the bioeconomic parameters and the simulations of the optimal or suboptimal paths.

To help solve the optimization model, a dynamic multi-dimensional optimization technique based on the optimal control theory was formulated. The optimization problem then reduced to an initial-value problem involving a system of nonlinear first order ordinary differential equations. Due to the absence of the terminal condition and the relaxation of the transversality condition, the solution obtained cannot be regarded as 'true' optimum, but rather suboptimum or near optimum.

The final empirical model was applied to the North Sea commercial fisheries. Six main demersal species and three main pelagic species were chosen to illustrate the applicability of the model. The data utilised were mainly secondary data published by ICES and MAFF. For comparative purposes, two measures of fishing effort were used — hours fishing and ton-hours fishing. The first measure of fishing effort corresponds to the number of hours the vessels were in the water and fishing, while the second measure also includes the vessel's characteristic in term of its average gross registered tonnage (GRT).

Taking bottom otter trawl as a 'standard fishing vessel', composite directed fishing effort for each species under investigation was computed, followed by empirical estimations of the bioeconomic parameters by ordinary least square regressions, and thus establishing the 'probable' nature of the biological interdependencies between species. The estimated parameters also made it possible to estimate the stock level of individual species for the period covered by the data. This was followed by a computer simulation using the estimated parameters to determine the dynamic suboptimal paths for the North Sea fisheries for cases subjected to no constraint, lower constraints only and both lower and upper constraints.

Initially, an attempt was made to solve the initial-value problem by the Numerical Algorithm Group

(NAG) Library Routine but without much success. The NAG routine normally works well for a well-behaved systems. However, complications usually arise for 'stiff' or badly scaled system as well as for system with solution containing rapidly decaying components.

As an alternative, a simpler less complicated routine written in FOTRAN 77 and based on the Runge-Kutta method of step-size four and Simpson's 1/3 Rule was used. The computing times varied from about ten minutes for the computation of the suboptimal paths to about twenty five minutes for the computation of the present value.

An examination of the sensitivities of these suboptimal paths to increases in discount rate, unit price and unit cost was also carried out.

A few regulatory measures which seemed capable of directing the fishing activity to a desired level, at least in principle, were briefly reviewed. This was followed by a glance at the fishery managements at the national and international levels.

8.2 Findings And Comparisons

Although the coefficients estimated in the model for the two measures of fishing effort possessed the desired signs, their generally low t-statistic values suggested they were mostly not statistically significant. These results apparently highlighted the difficulties encountered in determining the growth

process and the exact nature and degree of the biological interdependencies between species when using data from commercial fisheries. The results however did indicate the existence of the biological interdependencies between species although the probable type of species interactions differed for the two measures of fishing effort as well as from those suggested by Gulland (1987). The magnitudes of these species interactions were in general relatively low in comparison with their relative growth rates.

The estimated stock levels based on fishing effort measured in hours fishing appeared to be more comparable with estimates obtained from other studies than those estimated by fishing effort measured in ton-hours fishing. The later measure appeared to indicate lower estimates for most of the species stock levels. This seems to suggest an overestimate of the catchability coefficients associated with this fishing effort.

The estimated system of price demand functions agreed with the theoretical assumption of a linearly decreasing function of the harvest. All the parameters assumed the correct expected signs. The R^2 and t-statistic values of the regressions were generally high. However, despite the correctly (negatively) sloped demand functions, the respective changes in unit price with respect to harvest were generally small. This might justify the widely adopted assumption of a constant unit price in most studies.

Unit costs relating to each composite fishing effort directed at each species were estimated from the revenue per unit of fishing effort data where all the revenues and hence the unit costs were expressed in terms of 1975 unit prices of species landed in United Kingdom. These estimated unit costs were found to differ for both measures of fishing effort as well as for each species. Some fisheries appeared to reach or approach bioeconomic equilibrium early in the period while others later in the period.

Most of the solutions associated with the cases of no constraint and lower constraints only were found to be unfeasible. In the first case, the solutions diverged rapidly in both directions while in the second case, some of the harvest levels exceeded the corresponding biomass levels, thereby causing rapid depletion of most of the species.

For the case of both upper and lower constraints, the suboptimal solution obtained from the maximization of the present value for the two measures of fishing effort suggested the eliminations of some species (but not necessarily the same species), harvesting some species at their bioeconomic equilibrium levels, harvesting some species at some economically profitable levels and periodic harvesting of some species.

The first fishing effort ('000HF) suggested complete elimination of one or more of the competing

species. Of the ten pairs of competing species only one pair remained uneliminated. The second fishing effort ('000TH) however suggested that elimination of one or more symbiotic species could also lead to the elimination of the remaining common symbiotic partners.

Although the suboptimal paths for the uneliminated species (except species 10) associated with the first fishing effort appeared to reach a steady equilibrium situation where the biomass and harvest levels were kept approximately constant after some initial transient period, the suboptimal paths associated with the second fishing effort appeared in general to exhibit significant perturbations — in most cases it seemed to correspond to a damped harmonic motion. The second fishing effort also suggested a much lower suboptimal levels (of biomass and hence harvest) than the first fishing effort. As a result, the fishing mortalities for the uneliminated species were much higher for the second fishing effort — greater than 0.70 for most species. This is not a favourable situation. A slight increase in the harvest rate might drive the stock level below its 'critical recovery' level. The fishing mortalities in the case of the first fishing effort (except for species 10) varied in a more favourable range from a low 0.03 to a relatively high 0.23. The total annual economic profit generated and the maximum present value were both greater in the case of the first fishing effort than the second.

The low suboptimal levels, the high fishing mortalities and the low net economic returns suggested that despite the inclusion of the vessel's characteristic in the form of gross registered tonnage, the ton-hours fishing is a less satisfactory measure of fishing effort than the popular hours fishing.

Having described the suboptimal stock and harvesting paths, an examination of the species sensitivities to a number of economic parameters was carried out. The suboptimal harvests levels were in general quite sensitive to changes in the corresponding stock levels. However, the sensitivities of the suboptimal stock levels to changes in the discount rate were found to be less conclusive in the case of second fishing effort. While the stock levels and hence the harvest levels in the case of first fishing effort generally decreased in response to increases in discount rate, responses by the stock and harvest levels in the case of second fishing effort varied from species to species as well as from period to period — decreasing for some species in some periods while remaining unchanged or increasing for some other species, followed by opposite responses in later periods. The total annual economic profits for both cases of fishing effort were found not to be very sensitive to changes in discount rate although the present value decreased significantly for both cases.

The harvest and stock levels were found to be sensitive to changes in the unit price and unit cost. In the case of the first measure of fishing effort, responses by the predator and prey species were consistent with the theoretical expectations, while the symbiotic partner appeared to be less sensitive. The stock level of the symbiotic species (species 8) in this case remained relatively high and the long run suboptimal harvest level remained unchanged at the bioeconomic equilibrium level. The competitive species however exhibited periodic suboptimal paths and thus a less conclusive responses.

In the case of the second measure of fishing effort, responses by the predator and prey species appeared to be lagging 1-2 years behind. In contrast to the first case, the competitive species in this case was found to be sensitive in the long run to changes in its competitive partner's suboptimal levels.

At this point it would be desirable to compare the suboptimalities obtained in this study to that obtained in other studies. Contrary to some results for similar aggregated models (of a single species) studied by Clark (1971, 1976, 1985) and reviewed in Chapter 2, the transitions from the initial levels to the long run optimal (or suboptimal) equilibrium levels need not necessarily involve radical measures such as maximum harvesting and zero harvesting. At each time period the stock and harvest

levels adjusted relatively 'smoothly' to their respective optimal (or suboptimal) equilibrium levels.

However, these 'smooth' adjustments in most cases 'overshot' and/or 'undershot' the suboptimal levels during the early periods before finally settling at the long run suboptimal levels. This striking aspect of approach paths is also contrary to the one suggested by Clark and Munro (1975) and Clark (1976, 1985) for a nonlinear single species fishery model with variable unit price which also suggested a relatively smooth path but without any possibility of 'overshooting' and/or 'undershooting' the long run optimal or suboptimal level.

One of the reasons why the 'most-rapid' (or 'bang-bang') approach path does not apply here is that in a multispecies environment not all species can be immediately reduced to any desired levels simultaneously. While some species can be reduced to the desired (optimal or suboptimal) levels immediately, some other species might require several harvesting periods before reaching their respective optimal or suboptimal levels. Furthermore, the most-rapid-approach path is mostly associated with a linear single species fishery model. Nonlinear models on the other hand can produce very complex results, and extending it to a nonlinear multispecies fishery model will not only produce very complex but also unpredictable results. In addition, it should also be noted that for some species the long

run optimal or suboptimal levels might be periodic with the stock and harvest levels increasing and decreasing every few years.

Theoretical examinations of some of the major fishery regulations revealed that despite the ability of these regulations to direct fishing activity to the desired level, the fishery, if entry remains unrestricted, will still in the long run approach the open-access bioeconomic equilibrium level with complete dissipation of economic rents. Exception to this is the regulation associated with transferable fishing rights. Under this regulation, fishermen (or firms) are allocated fishing rights in the form of transferable quotas (harvests). This gives rise to the creation of market for transferable fishing rights which finally leads to an efficient reallocation of resources with the fishery being operated by the relatively low-cost fishermen.

Following its accession to EEC in 1973, most of the fishery regulations in UK were subjected to the approval of the European Committee. At this international (EEC) level, the main method of fishery regulation and control adopted has continued to be that of the catch quotas which are closely linked to the static concept of maximum sustainable yield (MSY). The simple and clear concept of MSY make it more favourable to politicians and fishermen than the 'more complex' concepts of economic or dynamic optima. Furthermore,

MSY seems to be the only single criterion in which several nations can agree upon -- what is economically optimal for one nation need not be economically optimal for another nation.

Entry, however still remains unrestricted (to the EEC member countries). As a result, the catch quota scheme adopted by the Committee was less successful in conserving the depleting stocks. Additional measures such as restricting entry or its equivalent need to be negotiated, agreed on and implemented if more successful outcomes are to be realised.

8.3 Scope For Further Reasearch

The model developed in the study can further be improved and extended in a number of ways. Fishing vessels are constantly being upgraded and modernised. These changes in fishing technology are likely to affect the fishing power of the fishing vessels and hence the catchability coefficients. Inclusions of other economic inputs such as labour and capital, whenever data permitted, in the harvest production functions with variable catchability coefficients will realistically improved the model.

Most of the fish species are migratory in nature and their distributions are not subjected to political or regional boundaries. Some species tend to congregate to some areas during certain times of the year and disperse to other areas at other times of the

year. The possibility of incorporating the migratory aspect into the model merits further investigation.

The model studied here is only a subset of a larger model. The processing and marketing sectors as well as the economic behaviour of the fishermen for example were excluded in the study. A detailed study of these sectors and their impacts on the optimal stock and harvest levels represents another scope for further research.

The fishery regulations and management also merits further detailed study. What constitute to an optimal fishery regulation remains vaguely defined. At the international level, despite the acceptance of the catch quota as a management tool, the allocation of quotas to member countries had been the subject of long negotiations. Alternative criteria -- biological, economic, political and social -- of an 'optimal' allocation of quotas need to be formulated. At the same time, matters concerning the transboundary character of the fishery also need to be considered.

The aggregate nature of the data has caused considerable simplifications to the model. Thus a more disaggregate model, for example age or size specific would seem more appropriate. However, such model would find little practical applicability if the empirical data continue to remain aggregated. This does not however deny the need for such model and its usefulness in fishery studies.

The effects of uncertainties and random fluctuations were some of the factors ignored in the study. To account for these effects calls for the transformation of the deterministic model to a stochastic model. Analysis of the stochastic model and result(s) should prove to be as equally interesting as the deterministic case.

Although the above topics appeared to be best analysed separately, it should be emphasised that from the fisheries point of view most of these topics, if not all, are closely interrelated.

8.4 Conclusions

This work has contributed and advanced the fishery studies in many ways. The traditional single species model was extended to a more general multispecies fishery model by incorporating the biological and economic aspects of interdependency. The unrealistic fishery exploitation of single species by single fishing effort was replaced by a multispecies-multieffort scenario. Instead of the commonly adopted assumptions of constant unit price and zero cost of harvesting, the study assumed a price demand function of finite price elasticity of demand and a constant unit cost of fishing effort, thereby making the unit cost of harvesting inversely dependent on the stock size -- a more realistic assumption.

The empirical results indicate that the model developed in the study is quite robust. Future trend in landings may indicate not only changes in stock sizes but also changes in fishing efficiency, and hence changes in the model's estimated coefficients. These changes can easily be accommodated by performing the regressions every few years as more recent data become available. Thus new estimates for the model's parameters and stock sizes can be made and hence a new updated optimal or suboptimal strategy.

Although the study focuses on multispecies fishery, the model can be easily modified so as to be equally applicable to other self-renewable natural resources such as wild life and forestry. A modified version which identifies the population according to sex, age or size would be appropriate for wild life model, while an age or size specific with no species interaction term version would best suit a forestry management model.

It should also be reemphasised that throughout this study the available data had placed constraints on the forms of the model and submodels adopted. Subject to these data constraints, the empirical results in general seemed to suggest that estimates using hours fishing as a measure of fishing effort are slightly preferable than those using ton-hours fishing.

Finally, the model developed has provided a methodology not only for analysing the biological and economic factors which are interdependent and interact with each other but also for identifying the dynamic optimal or suboptimal paths in a multispecies-multieffort fishery with limited biological and economic information. It is anticipated that the model will be extended and proved beneficial to others engaged in studies under similar data constraints.

APPENDIX A

Estimation of hours fishing by German Bottom Otter Trawls

Method of Estimation: Ordinary Least Square (OLSQ)

GRT (0-150)

Linear: $HF = 19.389(DF) - 6.9129$; $R^2 = 0.9998$
(129.60) (-0.048) D-W = 3.099

Loglinear: $\log(HF) = 0.9918\log(DF) + 3.0162$; $R^2 = 0.9998$
(131.11) (69.867) D-W=2.158

Exp: $\log(HF) = 0.00226(DF) + 6.927$; $R^2 = 0.8759$
(4.603) (14.73) D-W=1.519

GRT (151-300)

Linear: $HF = 15.285(DF) - 111.22$; $R^2 = 0.9985$
(45.252) (-0.483) D-W = 2.244

Loglinear: $\log(HF) = 1.0477\log(DF) + 2.3632$; $R^2 = 0.9838$
(13.507) (6.205) D-W=1.640

Exp: $\log(HF) = 0.00422(DF) + 5.1211$; $R^2 = 0.9180$
(5.797) (10.315) D-W = 2.244

GRT (600-1000)

Linear: $HF = 13.965(DF) - 0.010118$; $R^2 = 0.9953$
(35.722) (-0.00117) D-W = 2.867

Loglinear: $\log(HF) = 1.0616\log(DF) + 2.4398$; $R^2 = 0.9793$
(16.853) (17.213) D-W=1.414

Exp: $\log(HF) = 0.0771(DF) + 3.2186$; $R^2 = 0.7674$
(4.449) (8.365) D-W = 2.934

(Numbers in parentheses refer to the t-statistics, R^2 is the coefficient of multiple determination or correlation, and D-W is the Durbin-Watson statistics)

APPENDIX B

Regression Results for Estimation of Parameters

(Fishing Effort Measured in '000 Hours Fishing)

$$LiT = (1/T)\ \ln\ [U(i,t+T)/U(i,t)];$$

$$i = 1,\ldots,10 \quad \text{and} \quad T = 1,\ldots,5.$$

$$L15 = \underset{(0.205)}{0.2678} - \underset{(-0.4604)}{3.9723(10^{-3})U(1,5)} + \underset{(0.8187)}{4.3319(10^{-2})U(6,5)}$$

$$+ \underset{(1.8436)}{1.0061(10^{-2})U(7,5)} - \underset{(-0.6389)}{1.6410(10^{-5})E(1,5)}$$

$$R^2 = 0.6823; \quad F(4,7) = 3.76; \quad D\text{-}W = 1.9760$$

$$L24 = \underset{(3.414)}{1.8032} - \underset{(-7.6854)}{2.3699(10^{-2})U(2,4)} - \underset{(-4.8860)}{7.3967(10^{-3})U(4,4)}$$

$$+ \underset{(3.3342)}{1.6299(10^{-2})U(5,4)} - \underset{(-4.0414)}{9.0051(10^{-2})U(6,4)}$$

$$+ \underset{(0.5487)}{1.9968(10^{-3})U(7,4)} + \underset{(0.2066)}{3.6751(10^{-3})U(8,4)}$$

$$+ \underset{(2.1028)}{3.6218(10^{-2})U(9,4)} - \underset{(-0.3880)}{1.0899(10^{-3})U(10,4)}$$

$$- \underset{(-5.3098)}{2.8800(10^{-5})E(2,4)}.$$

$$R^2 = 0.9949; \quad F(9,2) = 42.99; \quad D\text{-}W = 3.4028$$

$$L34 = \underset{(1.695)}{1.0547} - \underset{(-5.8068)}{2.7352(10^{-3})U(3,4)} + \underset{(1.5803)}{5.3907(10^{-2})U(6,4)}$$

$$- \underset{(-2.5411)}{7.3414(10^{-2})U(9,4)} - \underset{(-1.3211)}{4.2750(10^{-5})E(3,4)}$$

$$R^2 = 0.8653; \quad F(4,7) = 11.24; \quad D\text{-}W = 2.6358$$

$$L42 = \underset{(1.205)}{1.9589} + \underset{(0.6002)}{0.1148U(2,2)} - \underset{(-0.3952)}{1.8753(10^{-2})U(4,2)}$$

$$+ \underset{(0.9523)}{7.7629(10^{-2})U(6,2)} - \underset{(-1.6328)}{4.2129(10^{-2})U(7,2)}$$

$$+ \underset{(0.5702)}{4.7270(10^{-3})U(9,2)} - \underset{(-0.5390)}{2.4485(10^{-3})U(10,2)}$$

$$- 3.5828(10^{-5})E(4,2)$$
$$(-2.1787)$$

$R^2 = 0.6307$; $F(7,6) = 1.46$; D-W = 1.9378

$$L54 = 3.4874 - 9.6698(10^{-2})U(2,4) - 4.8555(10^{-2})U(5,4)$$
$$(2.027) \quad (-0.7996) \qquad\qquad (-2.8075)$$

$$- 0.1251U(6,4) - 1.3600(10^{-2})U(7,4)$$
$$(-1.6229) \qquad (-1.2333)$$

$$- 0.1097U(9,4) + 6.1919(10^{-3})U(10,4)$$
$$(-2.0095) \qquad (2.2359)$$

$$- 1.5981(10^{-5})E(5,4)$$
$$(-0.2771)$$

$R^2 = 0.8270$; $F(7,4) = 2.73$; D-W = 3.1097

$$L63 = 34.896 - 0.58506U(1,3) - 0.61315U(2,3)$$
$$(1.276) \quad (-0.8789) \qquad (-1.4349)$$

$$- 0.18536U(3,3) - 3.0533(10^{-3})U(4,3)$$
$$(-1.2742) \qquad (-0.1871)$$

$$- 3.3698(10^{-2})U(5,3) - 0.27915U(6,3)$$
$$(-1.6288) \qquad (-1.0884)$$

$$- 5.9574(10^{-2})U(7,3) - 4.4659(10^{-2})U(8,3)$$
$$(-0.8006) \qquad (-0.1201)$$

$$- 0.88229U(9,3) - 4.4941(10^{-2})U(10,3)$$
$$(-1.3292) \qquad (-0.6449)$$

$$- 4.3707(10^{-5})E(6,3)$$
$$(-1.0415)$$

$R^2 = 0.9674$; $F(11,1) = 2.70$; D-W = 3.3023

$$L74 = 11.832 - 0.27499U(1,4) + 0.19611U(2,4)$$
$$(20.819) \quad (-15.128) \qquad (16.374)$$

$$- 2.0654(10^{-2})U(4,4) + 5.1267(10^{-2})U(5,4)$$
$$(-13.150) \qquad (10.835)$$

$$- 0.34694U(6,4) - 3.2910(10^{-2})U(7,4)$$
$$(-21.714) \qquad (-10.892)$$

$$+ 3.8738(10^{-2})U(8,4) - 0.41028U(9,4)$$
$$(2.6470) \qquad (-26.602)$$

$$- 4.8741(10^{-2})U(10,4) - 1.0385(10^{-5})E(7,4)$$
$$(-20.621) \qquad (-6.1133)$$

$R^2 = 0.9998$; $F(10,1) = 908.2$; D-W = 2.9864

$$L82 = 0.63517 + 5.0776(10^{-2})U(2,2) + 1.0097(10^{-2})U(6,2)$$
$$(0.5485) \quad (0.3659) \qquad (0.1022)$$

$$- 2.6889(10^{-2})U(8,2) - 1.7218(10^{-2})U(9,2)$$
$$(-1.5098) \qquad (-0.1903)$$

$$+ 2.9954(10^{-2})U(10,2) - 5.8490(10^{-6})E(8,2)$$
$$(1.5942) \qquad (-0.1598)$$

$R^2 = 0.5573$; $F(6,7) = 1.49$; D-W = 1.6294

$$L93 = 2.4874 - 4.1331(10^{-2})U(2,3) + 2.1433(10^{-3})U(3,3)$$
$$(2.992) \quad (-1.2362) \qquad (0.2434)$$

$$+ 5.4976(10^{-3})U(4,3) - 2.8607(10^{-2})U(5,3)$$
$$(5.7168) \qquad (-8.5305)$$

$$- 8.4792(10^{-2})U(6,3) - 2.9447(10^{-3})U(7,3)$$
$$(-11.932) \qquad (-0.4648)$$

$$- 0.31053U(8,3) - 0.17311U(9,3)$$
$$(-15.722) \qquad (-7.7078)$$

$$+ 3.8902(10^{-2})U(10,3) - 8.8135(10^{-7})E(9,3)$$
$$(30.007) \qquad (-9.2051)$$

$R^2 = 0.9998$; $F(10,2) = 813.5$: D-W = 3.0211

$$L102 = 2.1669 + 2.5131(10^{-2})U(2,2) - 4.2771(10^{-3})U(4,2)$$
$$(3.338) \quad (0.3407) \qquad (-1.6103)$$

$$+ 2.2778(10^{-2})U(5,2) - 5.6218(10^{-2})U(6,2)$$
$$(1.6657) \qquad (-1.8317)$$

$$- 1.5776(10^{-2})U(7,2) - 7.8545(10^{-3})U(8,2)$$
$$(-2.2807) \qquad (-0.1159)$$

$$- 3.1952(10^{-2})U(9,2) - 1.1342(10^{-2})U(10,2)$$
$$(0.7296) \qquad (-0.9634)$$

$$- 2.4874(10^{-5})E(10,2)$$
$$(-1.8439)$$

$R^2 = 0.8887$; $F(9,4) = 3.55$; D-W = 2.1394

(Numbers in parentheses refer to the t-statistics).

APPENDIX C

Regression Results for Estimation of Parameters

(Fishing Effort Measured in '000 Ton-Hours Fishing)

LiT (i=1,...,10; T=1,...,5) as in Appendix B.

$$L12 = \underset{(0.651)}{1.2671} - \underset{(-0.6167)}{1.1226U(1,2)} + \underset{(1.1674)}{22.440U(2,2)}$$

$$+ \underset{(0.1651)}{0.52915U(5,2)} - \underset{(-0.3309)}{0.87603U(7,2)} - \underset{(-0.7257)}{7.2522U(9,2)}$$

$$- \underset{(-0.5171)}{2.0733(10^{-7}E(1,2)}$$

$R^2 = 0.3975$; $F(6,7) = 0.77$; D-W = 1.6897

$$L24 = \underset{(14.783)}{2.3080} + \underset{(9.5600)}{15.156U(1,4)} - \underset{(-0.9227)}{1.9250U(2,4)}$$

$$- \underset{(-8.1833)}{0.75495U(4,4)} + \underset{(9.9951)}{3.9548U(5,4)} - \underset{(-13.406)}{61.486U(6,4)}$$

$$- \underset{(-10.347)}{4.2873U(7,4)} + \underset{(1.5639)}{5.0968U(8,4)} + \underset{(1.2527)}{1.0211U(9,4)}$$

$$+ \underset{(3.7712)}{1.4391U(10,4)} - \underset{(-2.6549)}{5.0716(10^{-8})E(2,4)}$$

$R^2 = 0.9995$; $F(10,1) = 183.7$; D-W = 3.4158

$$L32 = \underset{(0.934)}{1.2922} - \underset{(-1.3191)}{3.0328U(3,2)} - \underset{(-0.4500)}{0.81451U(7,2)}$$

$$- \underset{(-1.4353)}{6.6379U(9,2)} - \underset{(-1.2976)}{0.31509U(10,2)}$$

$$- \underset{(-0.3828)}{2.3633(10^{-7})E(3,2)}$$

$R^2 = 0.5540$; $F(5,8) = 1.99$; D-W = 2.0982

$$L43 = \underset{(0.645)}{1.0384} + \underset{(0.4525)}{7.8262U(2,3)} - \underset{(-1.6982)}{1.1613U(4,3)}$$

$$- \underset{(-1.4940)}{3.5507U(6,3)} - \underset{(-1.2405)}{2.5717U(7,3)} + \underset{(0.2106)}{1.9055U(9,3)}$$

$$- 7.3993(10^{-7})E(4,3)$$
$$(-1.7240)$$

$R^2 = 0.7728$; $F(6,6) = 3.40$; D-W = 1.6679

$$L54 = 5.0996 + 36.351U(1,4) + 22.799U(2,4)$$
$$(1.776) \quad (2.6147) \quad (1.2773)$$

$$- 5.2795U(5,4) - 103.73U(6,4) - 1.0849U(7,4)$$
$$(-1.8538) \quad (-2.1546) \quad (-3.0193)$$

$$- 21.130U(9,4) + 2.1143U(10,4)$$
$$(-2.4073) \quad (2.2998)$$

$$- 5.0462(10^{-7})E(5,4)$$
$$(-0.8533)$$

$R^2 = 0.8488$; $F(8,3) = 2.10$; D-W = 3.2496

$$L64 = 2.7441 + 13.779U(2,4) + 0.67806U(4,4)$$
$$(0.764) \quad (0.6114) \quad (0.7972)$$

$$+ 1.9422U(5,4) - 4.6828U(6,4) - 1.0304U(7,4)$$
$$(1.2743) \quad (-1.0781) \quad (-0.3902)$$

$$- 9.5700U(9,4) - 0.26105U(10,4)$$
$$(-0.6780) \quad (-0.5046)$$

$$- 1.7590(10^{-7})E(6,4)$$
$$(-0.3432)$$

$R^2 = 0.7933$; $F(8,3) = 1.44$; D-W = 2.2226

$$L72 = 4.9070 + 186.94U(1,2) - 130.09U(2,2)$$
$$(1.293) \quad (2.4400) \quad (-2.1554)$$

$$- 35.121U(3,2) - 8.5231U(4,2) + 1.2861U(5,2)$$
$$(-2.3444) \quad (-2.0471) \quad (0.2847)$$

$$- 43.189U(6,2) - 44.337U(7,2) - 150.25U(8,2)$$
$$(-1.5289) \quad (-2.1594) \quad (-2.4600)$$

$$- 4.9567U(9,2) + 15.532U(10,2)$$
$$(-0.3813) \quad (3.0233)$$

$$- 7.5634(10^{-7})E(7,2)$$
$$(-0.7482)$$

$R^2 = 0.9708$; $F(11,2) = 6.04$; D-W = 3.6202

$$L85 = 0.95016 + 29.787U(2,5) - 3.5173U(7,5)$$
$$(1.990) \quad (0.6940) \quad (-0.6832)$$

$$- 1.7701U(8,5) - 3.9203U(9,5) + 2.1224U(10,5)$$
$$(-0.6416) \quad (-0.2902) \quad (0.7260)$$

$$- 1.1476(10^{-7})E(8,5)$$
$$(-1.0943)$$

$$R^2 = 0.7563; \quad F(6,5) = 2.59; \quad D\text{-}W = 2.5484$$

$$L93 = 1.0510 + 114.94U(1,3) - 104.88U(2,3)$$
$$(6.547) \quad (4.6822) \quad (-4.3793)$$

$$- 25.337U(3,3) - 1.5028U(4,3) - 7.9008U(5,3)$$
$$(-4.7378) \quad (-1.5218) \quad (-5.0061)$$

$$- 3.2525U(6,3) - 26.390U(7,3) - 119.03U(8,3)$$
$$(-0.4384) \quad (-5.0169) \quad (-5.4091)$$

$$- 14.784U(9,3) + 14.665U(10,3)$$
$$(-8.2044) \quad (5.6135)$$

$$- 1.3014(10^{-8})E(9,3)$$
$$(-9.0618)$$

$$R^2 = 0.9992; \quad F(11,1) = 119.4; \quad D\text{-}W = 3.1782$$

$$L104 = 2.9978 + 70.956U(2,4) + 2.6783U(3,4)$$
$$(1.627) \quad (2.8083) \quad (0.5852)$$

$$+ 7.0391U(5,4) - 60.555U(6,4) - 8.1315U(7,4)$$
$$(3.8201) \quad (-1.7393) \quad (-2.1773)$$

$$+ 32.229U(8,4) - 16.960U(9,4) - 5.1412U(10,4)$$
$$(2.2688) \quad (-1.4662) \quad (-3.1616)$$

$$- 7.2903(10^{-7})E(10,4)$$
$$(-0.9480)$$

$$R^2 = 0.\ 9830; \quad F(9,2) = 12.84; \quad D\text{-}W = 2.9682$$

(Numbers in parentheses refer to the t-statistics)

APPENDIX D

Regression Results for the Price (Demand) Function

$$P(i) = p_o(i) - b(i)h(i), \quad i=1,...,10.$$

$P(1) = 550.30 - 1.9547(10^{-3})h(1)$; $R^2 = 0.8215$
(18.193) (-6.7831) D-W = 1.147

$P(2) = 1853.90 - 2.9319(10^{-2})h(2)$; $R^2 = 0.6509$
(15.031) (-3.8621) D-W = 0.836

$P(3) = 581.35 - 1.1570(10^{-3})h(3)$; $R^2 = 0.6228$
(4.4246) (-2.2257) D-W = 0.872

$P(4) = 301.38 - 2.1854(10^{-4})h(4)$; $R^2 = 0.8390$
(29.998) (-6.8481) D-W = 1.500

$P(5) = 201.93 - 3.8280(10^{-4})h(5)$; $R^2 = 0.6439$
(12.552) (-4.4596) D-W = 0.885

$P(6) = 168.08 - 2.4624(10^{-4})h(6)$; $R^2 = 0.7506$
(30.417) (-5.4865) D-W = 2.402

$P(7) = 216.34 - 2.2496(10^{-4})h(7)$; $R^2 = 0.7508$
(11.678) (-5.4894) D-W = 1.081

$P(8) = 41.473 - 1.9461(10^{-5})h(8)$; $R^2 = 0.7669$
(29.338) (-5.1303) D-W = 2.688

$P(9) = 69.953 - 5.8782(10^{-5})h(9)$; $R^2 = 0.4156$
(8.3884) (-1.6866) D-W = 2.144

$P(10) = 203.69 - 5.7802(10^{-5})h(10)$; $R^2 = 0.6900$
(25.686) (-6.9984) D-W = 1.189

(Numbers in parentheses refer to the t-statistics)

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