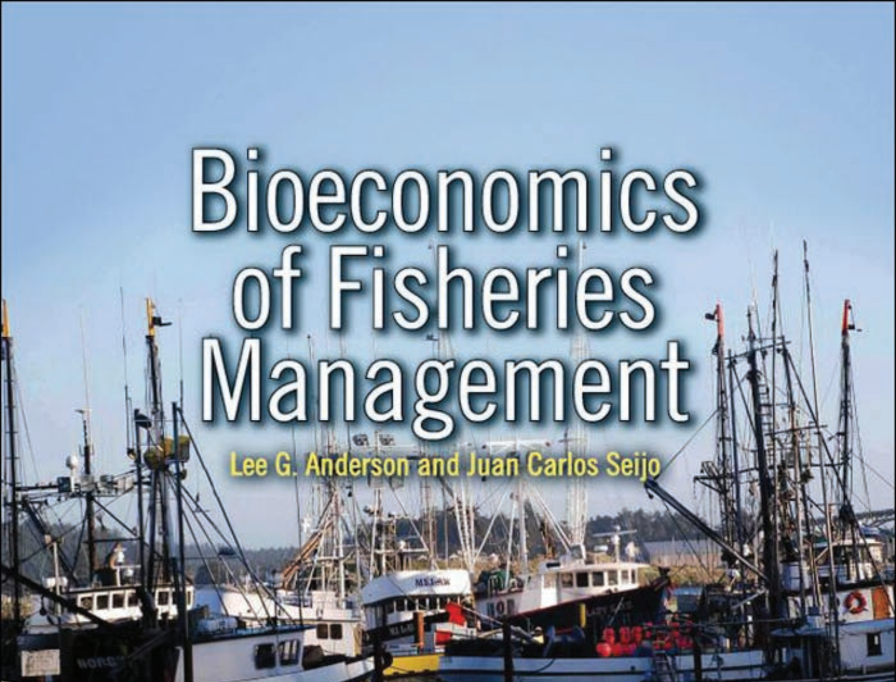
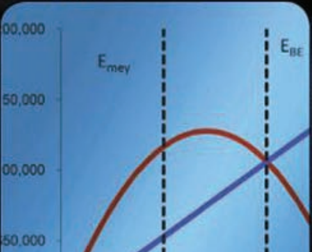


Bioeconomics of Fisheries Management

Lee G. Anderson and Juan Carlos Seijo



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Bioeconomics of Fisheries Management

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Preface

This book is the result of the long-time collaboration between the two authors. It began in the mid-1990s while team teaching a series of short courses on the Bioeconomics of Fisheries Management and Regulation in Mexico, Chile, and Taiwan. The idea of writing a book followed almost naturally. Like all such endeavors, it has been a long and arduous process because it proceeded simultaneously with our normal teaching and research activities and was marked by serious illnesses in both families. Anderson is responsible for Chapters 2, 3, 4, 6, and 7, while Seijo is responsible for Chapters 1 and 8 to 12. Seijo prepared the simulation model that is the basis for the age-class discussion in Chapter 5 and Anderson wrote the majority of the text for that chapter. He also made some modifications to the simulation model, mostly with respect to introducing a regulation analysis.

The authors are grateful for the support of their respective institutions and of Wiley-Blackwell. Most important, they are grateful to their wives and families for their patience and support during the much too long incubation period of this book.

The book is dedicated to Lee's best friend Sheila and to Juan Carlos' family and students.

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Bioeconomics of Fisheries Management

Chapter 1

Introduction

Systematic fisheries research that can develop and test hypothesis relating alternative management and regulation structures with fishery performance requires the integration of resource biology and ecology with the economic factors that determine fishers' behavior in space and time. The distinction between management and regulation will be discussed below. The inherent characteristics of fish resources create different contexts of human interdependencies, and thus the same institution or management or regulation structure can result in a different performance when applied to fisheries having different resource and community contexts. The degree of resource mobility in space and time as well as the degree of fishing autonomy of small-scale and industrial vessels provides direction to those human interdependencies in resource use.

Modern fisheries bioeconomics can provide insight into developing approaches to deal with the complexities of overcapacity and overexploitation in marine fisheries where most are affected by natural fluctuations, changing coastal ecosystem dynamics, and lack of solid governance. In this introductory chapter, we answer the basic question of why fisheries management is needed, and discuss the characteristics of fish stocks and the resultant participant behavior that prevents the market from optimally allocating this type of resource. We also define fisheries bioeconomics, and provide a short introduction to the topics covered in the book.

1.1 Why is fisheries management and regulation needed?

There are many reasons why fisheries utilization can be improved by controlling the activities of actual and potential participants. Given that this is a book on bieconomics, the lack of appropriate system of property rights is of particular importance. Although the topic cannot be discussed in detail here, it is generally agreed that in order to create incentives to put resources to their highest valued uses, property rights should have the following characteristics (Randall, 1981; Schmid, 1987; Scott, 1989, 2008; Anderson and Holliday, 2007):

- *Exclusivity:* This refers to the degree to which the outputs produced as a result of owning and using the resource for which the property right is defined are under the complete control of the owner to use or relinquish. Similarly, the degree to which all costs associated with the use of the resource is the responsibility of the owner. The ability to enforce these claims is an important aspect of exclusivity, and sometimes enforceability is listed as a separate characteristic. It also refers to the ability to use and manage the resource without outside interference.
- *Permanence:* This refers to the length of time that the right can be maintained. It is important because incentives for proper use will depend on how long the owner can claim benefits or be responsible for costs.
- *Security or quality of title:* This refers to the degree to which the right is free from involuntary seizure or encroachment.
- *Transferability:* This refers to the ability to transfer the right to someone else. This is also important for making it possible to put the resources to their highest valued use.

As will be discussed in more detail below, even in cases where there is active government intervention in fishery utilization under open access, these characteristics do not apply to fisheries resources, especially not to the degree that they do to other natural resources. Basically this means that participants have little incentive to utilize a fish stock so as to take full advantage of its reproductive potential. As we will demonstrate below, designing regulation procedures such that they provide incentives similar to those provided by property rights can prove very successful.

When thinking about fisheries management and regulation, it is important to consider other aspects and attributes of fisheries resources that can affect short- and long-term fishing behavior and exploitation patterns, both with and without regulation. Among these, high exclusion costs, high transaction costs (information costs and enforcement costs), free rider behavior, and a social trap situation must be acknowledged (Seijo *et al.*, 1998; Caddy and Seijo, 2005).

High exclusion cost. It means that the use of an existing fish stock cannot easily be limited to those who have the right to fish it. Just because there are provisions whereby only a specified number of participants are nominally allowed to fish does not mean that all others can be effectively excluded. Because of the mobility and migratory nature of most fish resources, enforcing rights and regulations in marine fisheries is not only logistically difficult but also very costly. Fisheries management and regulation involve *high enforcement or policing costs* in order to keep participation limited to permitted individuals and fishing activities limited to those that are permitted. For oceanic (and many shelf) fisheries, the areas to be policed are extensive, and conventional patrol vessel operations are ineffective and costly. Under these circumstances, a nonenforceable right becomes an empty right.

High information costs. The complexity of fisheries management is increased by the major uncertainties inherent in natural systems, as well as by a range of other biological, social, political, and economic factors, requiring a precautionary approach to fisheries management (FAO, 1996). In general, it is very expensive to obtain useful information sufficient enough to know what is the right management strategy and corresponding regulations even in the context of stakeholders' cooperation. In addition, the multidisciplinary nature of the required information to assess the state of the fishery and the ecosystem that sustains it require interdisciplinary approaches linking natural and social sciences. This book is an attempt to foster the needed interdisciplinary analysis in fisheries by merging biological and ecological principles and methods with the economics of fisheries to further develop the field of fisheries bioeconomics.

The difficulties in meeting the basic assumptions of exclusivity and low information and enforcement costs are serious obstacles to effective property rights allocation. The inherently high exclusion and transaction costs, the characteristics of fisheries described above, require us to look beyond the simple solution of providing for "proper allocation of individual rights." The allocation of resources between stakeholders is the problem area where progress is most urgently required, both nationally and internationally.

1.2 The social trap and free rider behavior in fisheries

In addition, it should be recognized that fisheries are usually confronted with a social trap situation that is directly related to the lack of exclusivity in the rights to open access fish stocks. Applying Shelling's (1978) terminology, a social trap exists when the micromotives of an individual fisher in the short run are not consistent with the macroresults he and other fishers desire in the long run. The short-run micromotives consist of catching as many fish as possible in order to increase individual marginal benefits, while the long-run desired macroresults may involve achieving the maximum economic yield or maximum sustainable yield. Uncertainty as to future stock availability determines that long-run results are usually dominated by short-run marginal benefits. Allowing for temporal fluctuations in resource productivity and preferences of resource use, a sustainable yield from a fishery will tend to be attainable only when the number of fishers is limited, and they act in concert to implement some form of effort regulation (Seijo, 1993). However, if the group is large, a fisher may be an unintentional free rider or a noncontributing user. This type of individual usually occurs when there is no voluntary collective action by the majority of community members to prevent resource depletion, and also when uncertainty exists as to stock abundance (which is the usual case in marine fisheries).

1.3 Stock fluctuations due to natural causes

Independently of fishing, stocks can also fluctuate in the short and long run because of natural causes. For pelagic resources, major stock fluctuations occurred even prior to human exploitation, as shown by the work of Soutar and Isaacs (1974). Productivity fluctuations related to the El Niño Southern Oscillation in the eastern Pacific have been documented by Lluch-Belda *et al.* (1989), and similar climatic forcing factors have been affecting marine production systems on the global level (Kawasaki, 1992; Klyashtorin, 2001). It should be pointed out that decadal periodicities are frequently mentioned in the fisheries literature (e.g., Zwanenberg *et al.*, 2002), but Klyashtorin (2001) suggests that natural cycles in the productivity of around 50–60 years' duration are likely to be dominant, and that long-term fluctuations are likely to be reinforced by climate change.

Modern fisheries bioeconomics should integrate principles, concepts, and analytical and numerical techniques to deal with the dynamics of natural fluctuations.

It should also be acknowledged that coastal fishery resources are also vulnerable to other human activities that may affect critical habitats and/or biological processes. In fact, the role of environmental change has become more evident in recent years as fisheries data series of all but the longest established fisheries exceed half a century in duration, but our ability to discriminate between natural environmental changes, the effects of fishing, and other human activities seems to remain poor.

Within this context, the problem of fisheries management, which comprises the choice of a target stock size and a harvest time path to achieve or maintain it, can be a difficult and complex process. However, just as troublesome is the problem of fisheries regulation which comprises the determination of how to control harvest such that the desired and actual catches in any year coincides. One of the problems is that although the regulation objective can be stated in terms of annual catch, as stated in the previous sentence, a fishery is not a static phenomenon, as evidenced by the time-path trajectories that will be shown in the initial chapters of the book. Human interventions or natural events that happen in one period can have repercussions in the future. This is also true of regulations. Human actions that are done in one period can have such effects on both the stock and fleet that will affect the efficacy of current regulations and the general ability to control harvest in the future.

In summary, the lack of an appropriate property right system is perhaps the main reason why fish stocks tend to be misused under an open access regime. However, there are other reasons as well, some of which are related to and exacerbated by the misspecification of property rights. A more complete analysis of this will be provided throughout the following discussion. We will describe below what exactly the "misuse" of fisheries resources really means, and elaborate on why it occurs under open access, and on the range of things that can be done to address the problem.

1.4 Fisheries bioeconomics

Fisheries bioeconomics (Clark, 1985; Anderson, 1986; Hannesson, 1993; Seijo *et al.*, 1998) is a field that integrates resource biology and ecology with the economics of fisher behavior, considering space, time, and uncertainty dimensions. The relative importance of including some or all of the above-mentioned dimensions in the bioeconomic modeling and analysis of fisheries will depend on the fishery-specific management questions, the degree of stock mobility and sensitivity to environmental factors, and the likely behavior of fishers over time and space.

In order to address the above definition of fisheries bioeconomics, this book covers the following set of topics. In Part I called Single Stock—Single Fleet Models, six chapters are presented in addition to this introduction. Chapter 2 presents the fundamentals of fishery bioeconomics with the aggregate Schaefer–Gordon model. The main purpose is to understand the open-access bioeconomic process that leads fisheries to biological and economic overexploitation and to answer the questions of what biologic and economic overexploitation means. And why will individual choice not lead to economic efficiency? In Chapter 3, we formally introduce the concept of fishery dynamics, which shows the analysis of how stock and effort change over time in response to biological and economic conditions. It also introduces a disaggregated model in order to consider the decision-making process of individual vessel operators. This disaggregated model provides a more robust picture of the exploitation of a fishery. It is especially important when considering the effects of regulation. Chapter 4 presents a formal mathematical discussion of the dynamic optimal utilization of a fish stock in the context of commercial utilization, showing the optimal combination of stock and fleet size and the necessary time path of moving from other combinations to the optimal one. In Chapter 5, the discussion is expanded to provide a better picture of population dynamics by presenting an age-structured format where recruitment, individual growth, and natural mortality are treated independently. For the most part, the economic and fishery management lessons that follow from the Schaefer model can be stated in terms of the age-structured model. In fact, although it requires numerical rather than analytical techniques, it is possible to derive sustainable revenue and cost curves as well as population equilibrium and economic equilibrium curves. It does provide something extra in that it allows for analysis of age at first capture regulations and for the peculiarities of different stock recruitment relationships. But for the most part, the purpose of introducing it is not to learn more fisheries economics per se. The purpose is to ensure that economic principles can be applied to answer management questions using a potentially superior bioeconomic model.

In Chapter 6, we discuss the tasks of fisheries management and regulation. The first one is the selection of what is the desirable amount of harvest to take, given the current biological and economic status of the fishery. The second is to implement regulations such that actual harvest corresponds to the desired harvest taking into account management agency and participant costs as well as the short- and long-term effects of how the regulations will affect participant behavior. We will call the first task fisheries management and the second task fisheries regulation. Chapter 7 describes, analyzes, and compares and contrasts the various types of regulations that have been and could be used to manage fisheries. It shows the short- and long-run bioeconomic effects of these regulations taking into account how participants will likely react and the biological and economic interconnections of fisheries utilization. This chapter stresses that the analysis of a regulated fishery is analogous to that of an open-access fishery. The difference is in demonstrating how the time paths will differ, given the constraints imposed by regulation.

In Part II, Multi-Stock—Multi-Fleet Models, and chapters dealing with ecosystems, space, seasonal and stochastic fluctuations, and uncertainty have been presented. Chapter 8 introduces a new section of the book where some of the assumptions of analytic and numerical bioeconomic developments presented for single species and single fleet distributed homogeneously over space in a deterministic context are relaxed. Managing fisheries with ecosystem considerations involves relevant ecological interdependencies among species along the trophic web. Understanding their dynamics may become essential to further understand fisher behavior over time. Nevertheless, how far bioeconomic modeling and analysis should go in incorporating multispecies and their bioecological interdependencies will depend on (1) the relevant fisheries and ecosystem management questions posed to address stock recovery and sustainability strategies within an ecosystem framework, (2) the bioecological and economic data availability for serious parameter estimation of increasingly complex mathematical models required to address the identified relevant questions, and (3) the assumptions and associated uncertainties of such complex models. With the selected species to be considered in the relevant ecosystem, we have to also consider the heterogeneity of fleets targeting or harvesting them incidentally over time.

Hence, in Chapter 9, we will expand on the single-species, single-fleet biomass dynamic and age-structured bioeconomic models discussed in Chapters 2 through 5 to consider multifleet and multispecies fisheries with ecological and/or technological interdependencies among species and fleets. In a parsimonious process toward an ecosystem approach to fisheries management, identifying and considering the relevant bio/ecological relationship present in a fishery or a set of interdependent fisheries becomes a priority. Also, of importance is to consider possible technological interdependencies among fleets and among fisheries. That is the situation of fleets that compete for a stock, multispecies fisheries that harvest incidentally stocks that constitute targets to other fishery, and sequential fisheries where fleets with heterogeneous fishing power, gear selectivity, and costs of effort affect different components of the population structure over time.

Chapter 10 reviews the need for understanding the spatial heterogeneity in marine resource abundance and the corresponding spatial behavior of fishing intensity over time. The recognition of the implications of dynamic pool assumptions in overestimating stock abundance is discussed together with spatial modeling efforts aimed at relaxing this unrealistic assumption for sedentary species and many low mobility demersal resources. Responsible spatial management and modeling of fisheries require understanding the spatial behavior of species with the corresponding abundance heterogeneity in space and time and the ecological interdependencies within an ecosystem framework. It also involves proper understanding of fisher behavior driving their spatial fishing intensity. This last aspect is fundamental to fisheries economics which focuses on the motivation of fisherman in their fishing behavior over space and time. This chapter discusses the use of marine-protected areas for spatially managing single stocks as well as for interdependent stocks in metapopulations with source–sink configurations.

Chapter 11 presents ways of incorporating seasonality and long-term patterns of fluctuating stocks in the bioeconomic analysis of fisheries. In the first part of this chapter, we address the problem of seasonal regulation of effort under open access using an age-structured bioeconomic model with seasonal spawning, hatching, and recruitment processes built in. In the second part, we model the long-term dynamics of stock fluctuations, using a periodically varying carrying capacity. We also present an age-structured bioeconomic model for environmentally driven fisheries that respond to long-term oceanic patterns of productivity and environmental conditions. This is done by using an environmentally driven recruitment function.

Finally, Chapter 12 deals with uncertainty and risk analysis in marine fisheries. We acknowledge that fisheries management in the last few decades has learned that population dynamics is affected by factors about which information is usually incomplete. Bio/ecological factors that play a role in population dynamics and bioeconomic analysis are often unknown or their relevance unclear. As shown in Chapter 9, fishing a specific target species may be affected by ecological as well as technological interdependencies occurring between species and fleets. Spatial complexities, like the ones presented in Chapter 10, involve not only understanding and estimating resource and fisher behaviour over space and time but also studying the dynamics of oceanographic processes dispersing larvae that will eventually settled in source or sink areas where habitat and food availability are critical for defining the dynamics of metapopulations. The extent to which population dynamics are affected by the surrounding ecosystem is often very complex and should be accounted for. How environmental fluctuations, as discussed in Chapter 11, affect fish populations on a local or global scale is largely unknown. Besides the observed periodicities of such fluctuations and the correlations with fish harvesting recently identified, the underlying cause–effect mechanisms are yet to be identified with reasonable certainty.

But not only should fisheries management acknowledge that fish population dynamics are complex and influenced by factors that are usually poorly understood, it should also recognize that fishers' behavior over space and time is difficult to predict and more so to effectively avoid or mitigate overexploitation and over capacity. Managing fisheries requires detailed knowledge regarding factors that influence fishing behavior, which in turn can vary depending on fishermen's cultural background and context, fishing technology used, and perceptions and strategic behavior affecting compliance to the regulatory scheme in place.

Another important part of the book is the series of exercises that have been developed to accompany, amplify, and expand on the material in the text. They are presented in the form of Excel spreadsheets that are prepared to produce graphical analyses. This allows for an understanding of how the analytics are affected by changes in the parameters. In many cases, simulation models are presented to show the dynamics of open access and regulated fisheries in more detail. In addition to being useful for pedagogical purposes, it is hoped that the simulation models can provide the springboard for further dynamic modeling studies.

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Chapter 2

Fundamentals of fisheries bioeconomics

2.1 Introduction

A fishery can be thought of as a stock or stocks of fish and the enterprises that have the potential to exploit them. It can be a very simple system where a fleet of similar vessels from a single port exploits a single stock of fish. Or it can be more complicated where fleets from different ports using differing technologies harvest fish from several stocks that are ecologically related. Throughout the course of this book, we analyze many different types of fisheries. The purpose here, however, is to provide a basic analysis with a very simple model. Even with the simplicity, the results will generally apply to the more complicated but more realistic systems. The fundamentals of a fishery can be described using Figure 2.1.

First, the fish stock, measured in terms of biomass, is the natural capital of the system. The items of interest are its ability to reproduce and provide new recruits, the growth rate of individuals, the natural mortality rate, and the rate of fishing mortality. The stock will increase if recruitment of new individuals and the growth of existing individuals add more to biomass than is removed by natural and fishing mortality.

Second, the fishing fleet is the man-made capital of a fishery; it harvests the stock in order to provide fish for the market and net returns to the fleet owners. The items of interest are the production function (the relationship between stock size, vessel activity, and harvest), the costs of inputs, and the price of fish. The size of the fleet will tend to vary with the sign and size of net returns. If gross returns are greater than all costs of production, the fleet will tend to increase. However, when the reverse is true, the fleet size will tend to decrease as owners look for other uses of their vessels or simply go out of business.

One of the purposes of fisheries bioeconomics is to show how a fishery will likely operate given these endogenous, but interdependent, changes in fleet and

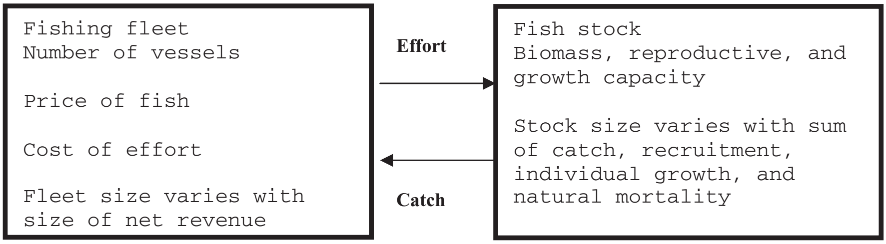


Figure 2.1 Fundamental components of a fishery.

stock size. It will be shown that left to its own devices a fishery will tend to operate such that "too much" fishing effort is produced with the result that the size of the fish stock will be "too low." The criteria for determining what is "too high" and "too low" are part of the story. The second purpose is to suggest and analyze procedures for regulating participants such that the desired level of effort is obtained. It should come as no surprise that accomplishing the second purpose is an ongoing process. Nonetheless, fisheries bioeconomics can be a very important tool in the development of practical fisheries management policy.

In order to understand the operation of a fishery, it is necessary to specify the relationships that describe the above-mentioned process. First, what are the population dynamics of the stock? How will the stock of fish change over time with and without fishing? Second, what is the harvest production function? What is the relationship between the inputs used and the amount of fish that will be harvested from a given stock size? Finally, given prices and costs, what is the relationship between the amount of effort produced and net returns from fishing.

As can be imagined, these relationships will differ from fishery to fishery, depending on the type of fish stock, the technique for harvest, the type of product and the market in which they are sold. In order to understand the behavior of a particular fishery, the relationships used in modeling the fishery must match those in the fishery to the extent possible given general knowledge and specific data availability. For pedagogical reasons, we start with some relatively simple assumptions regarding these relationships. This will make it easier to make some important points. As the discussion progresses, more and more complicated relationships are introduced.

2.2 The Schaefer logistic growth model

Fish stocks are commonly measured in terms of tons of biomass. The growth of a fish stock is the net effect of the weight of new individuals entering as a result of recruitment, the weight of individuals leaving the stock as a result of natural mortality due to old age, disease, or predation, and the increase in weight due to growth of individuals in the stock. The stock size will be increased when the effects of recruitment and individual growth are greater than the natural mortality, and vice versa. An equilibrium stock size will be achieved when increases in stock due to recruitment and individual growth are just balanced by the decrease due to natural mortality.

The Schaefer model is a simple mathematical formulation that is capable of capturing many of the elements of population stock dynamics of real-world fish stocks. It assumes that recruitment, individual growth, and natural mortality can be represented simultaneously by a logistic growth equation. The model is based on the work by Verhulst (1838), but it is usually attributed to Schaefer because of his early use of it in bioeconomic modeling. This model specifies that the instantaneous growth in stock biomass, X_t, can be represented in a differential equation as follows:

$$\frac{dX}{dt} = G(X_t) = rX_t\left(1 - \frac{X_t}{K}\right) \tag{2.1}$$

The parameter r represents the intrinsic growth rate, the rate at which the stock would typically grow with no external effects. The parameter K represents the carrying capacity of the environment, the largest size that can be achieved given food supplies, habitat, etc.

The first term in the equation, rX_t, shows that growth is proportional to stock size, but the second term, $[1 - (X_t/K)]$, adds the complexity that growth decreases with stock density, X_t/K, and when the stock size equals the carrying capacity, growth will fall to zero. The combined effect is an inverted U-shaped growth curve where growth initially increases with stock size but ultimately falls to zero. The maximum growth rate can be found by taking the first derivative of Equation 2.1, setting it equal to zero, and solving for X. Ignoring the time subscripts, we have

$$r - \frac{2rX}{K} = 0 \tag{2.2}$$

Solving for X obtains:

$$X_{\mathrm{MSY}} = \frac{K}{2} \tag{2.3}$$

Using the parameter set of Table 2.1 and substituting $K/2$ into Equation 2.1 show that the maximum growth rate will equal $rK/4$ or 7,500 tons, when r equals 0.3 and K equals 100,000. Figure 2.2 shows the shape of the growth curve. The maximum growth of 7,500 tons occurs at a stock size of 50,000 tons. The curve can be interpreted as follows. At lower stock sizes growth varies directly with stock size because recruitment increases, and the more individuals there are in the stock, the greater will be the effect on individual growth.

After a certain point, however, the stock will begin pushing against the environmental carrying capacity, which will reduce recruitment and individual growth and increase natural mortality. In this range, net growth is inversely proportional to stock size and eventually falls to zero.

Table 2.1 Parameter set for Schaefer logistic growth model.

	Symbol	Value
Biological parameters		
Intrinsic growth rate	r	0.3
Carrying capacity	K	100,000
Economic parameters		
Price of fish	P	\$17
Cost per unit of effort	C_E	\$25
Catchability coefficient	q	0.00005
Equilibrium values		
Maximum sustainable yield	Y_{MSY}	7,500
Bioeconomic equilibrium yield	Y_{BE}	6,228
Maximum economic yield	Y_{MEY}	6,851
Stock at maximum sustainable yield	X_{MSY}	50,000
Stock at bioeconomic equilibrium	X_{BE}	29,412
Stock at maximum economic yield	X_{MEY}	64,706
Effort at maximum sustainable yield	E_{MSY}	3,000
Effort at bioeconomic equilibrium	E_{BE}	4,235
Effort at maximum economic yield	E_{MEY}	2,118

The shape of the Schaefer growth curve depends on the absolute and relative sizes of the parameters, r and K. With the same K, a higher r will increase growth at all stock sizes, while with the same r, a higher K will increase the range over which the growth rate is positive and will increase the growth rate at all stock sizes.

A critical issue in fisheries management is what will happen to stock size over time. Although there are some nuances that become clear in later parts of this book, for most purposes, the size of an unexploited fish stock will change

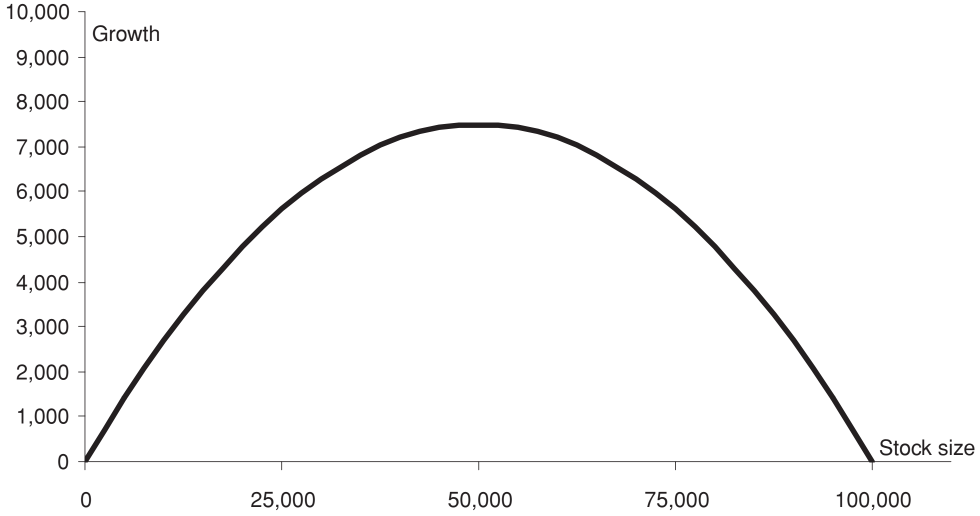


Figure 2.2 Schaefer logistic growth curve.

through time according to the following discrete relationship:

$$X_{t+1} = X_t + G(X_t) \tag{2.4}$$

That is, with no harvest, stock size next year is the sum of the stock size this year and growth generated by the stock during the period of observation. In terms of the Schaefer model, the stock will reach an equilibrium when X_t equals K, because $G(K) = 0$ and so $X_{t+1} = X_t$.

Of course, to find the exact time path of stock size, it is necessary to find the solution for the differential growth equation (Equation 2.1). Clark (1976) provides the solution for this equation:

$$X_t = \frac{K}{1 + c\,e^{-rt}} \tag{2.5}$$

where $c = (K - X_0)/X_0$. As demonstrated in the exercises given in the CD, the difference between the time paths generated by these two equations is quite small. The discrete equation is somewhat easier to use especially when harvest is considered, and it is used throughout the book.

Figure 2.2 shows the time path of stock growth assuming an initial stock size of 5,000 tons or 5% of maximum size given by the carrying capacity of the environment. The logistic form of the growth path can be clearly seen (Figure 2.3). When the stock is low, growth is low, and so stock size increases relatively slowly. When the stock is at medium levels, the growth rate increases and the time path of stock size becomes quite steep. However, as the stock approaches the carrying capacity, negative density-dependent effects slow the growth rate, and the final approach to K is a relatively flat curve. The shape of the curves shows a little about the population dynamics of fish stocks. But one point should be clear even at this early stage in the discussion. Time is an important aspect in fisheries management. If a fish stock is pushed lower than its maximum size for whatever reason, while it can regain that larger size, it will take time to do so even when there is no harvest. The amount of time it will take depends on biological characteristics, captured by the intrinsic growth rate in this simple model, and on how low the stock is pushed.

2.3 Schaeffer logistic growth with harvest

Consider now how harvest will affect the population dynamics of a fish stock. Using the discrete formulation, the periodic change in stock size with harvest can be represented as follows:

$$X_{t+1} = X_t + G(X_t) - \text{Harvest}_t \tag{2.4a}$$

Stock size next year will be equal to stock size this year plus growth this year minus catch this year. In this case, the stock will reach an equilibrium where $G(X_t) = \text{Harvest}_t$. This is a simple point, but it bears repeating given

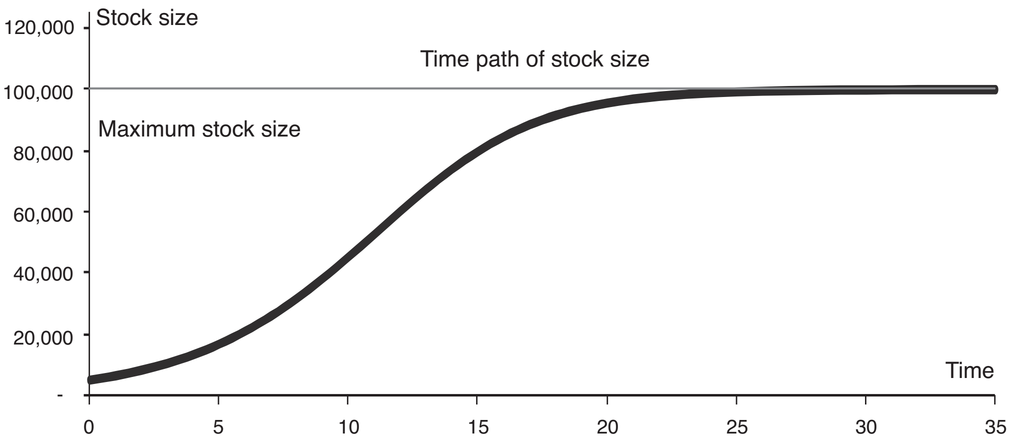


Figure 2.3 Logistic form of the time path of stock size.

its importance in all the analyses to follow. The adjustment of stock size until growth equals harvest is the equilibrating factor that causes the time path of stock size to move toward an equilibrium. If the harvest rate is changed, there will be a different equilibrium. It will occur at that stock size where growth equals the new harvest level.

Figure 2.3 shows the time path of stock size with and without harvest using the same parameters, assuming an initial stock size of 20,000 tons and a constant harvest equal to 3,000 tons. Two points are obvious. First, the time path with harvest is lower at every point in time than the time path without harvest. Second, an equilibrium is reached at a stock size that is less than the limit set by carrying capacity. The first point clearly shows an important trade-off that is a basic part of fisheries economics: How much should be caught now for current consumption and how much should be left in the water to grow. There is an opportunity cost of harvest in terms of stock size. It boils down to a choice between fish now and fish in the future. This is discussed in more detail below.

The second point follows from the basic logic of stock growth. In an unexploited fishery, an equilibrium will be achieved when the increase in biomass from recruitment and individual growth is just matched by the decrease due to natural morality. What is "going in" is equal to what is "going out." With fishing (Figure 2.4), there is another source of mortality. But again, an equilibrium will be achieved when the additions to biomass are equal to the removals. As pointed out above, this will occur at the stock size where the overall natural growth of the stock is equal to harvest.

To look at this a different way, a very naïve view that is sometimes put forth concerning sustainable harvest is "commercial fishing is okay as long as it does not affect the size of the stock in the ocean." But fishing will always affect stock size. In fact, in order to take advantage of the productivity of the natural environment, it is necessary to reduce the stock. When stock size is at

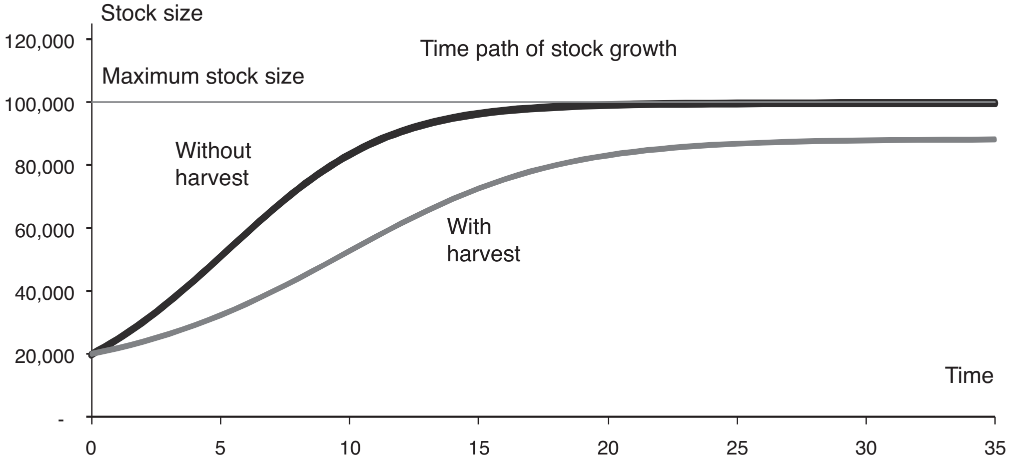


Figure 2.4 Time path of stock growth with and without harvest.

the carrying capacity level, stock growth ceases because of density-dependent effects. There is more competition for food and habitat as density (the size of the stock relative to the carrying capacity) increases. Reducing stock size and density allows for faster growth, which forms the basis for a sustainable harvest.

There are two important points here. First, there are many potential equilibrium stock sizes. We discuss this point further, using the population equilibrium and the sustainable yield functions below. A more important point is that it will take varying amounts of time to achieve a new equilibrium stock size. The management of fisheries needs to be considered in a dynamic sense. In many cases it is not very useful to think in terms of equilibrium stock sizes, or of changes in the equilibrium with changes in harvest levels. Often it is more useful to think of the time path of stock size as it moves toward an equilibrium. The shape of the path depends on the initial stock size, the parameters of the growth function, and the amount of harvest.

This demonstrates an important concept for long-run optimal management. The fish stock can be considered as a piece of capital that allows for the production of fish as a market product. It is possible to invest in the capital by taking a short-run cut in production. As with all investments, the point is to make sure that what is gained in the value of future production more than makes up for the loss in current production. This is discussed in more detail below, but it is critical to understand the importance of time when making stock adjustments.

2.4 A more formal analysis of commercial harvest

The above analysis discussed the basic relationship between growth and harvest in population dynamics. But harvest is the result of deliberative actions by participants in the fishery. To understand fisheries utilization, it will be necessary to understand what goes into the decisions to fish. Likewise, to properly think about fisheries management, we need to understand how these decisions are affected by various types of rules and regulations, and in turn, how this will affect the amount of fish taken and the size of the stock. This can be facilitated by introducing the concept of the fishery yield or production function. Annual yield can be viewed as a function of the size of the stock and the amount of fishing effort applied to it. For the moment, think of fishing effort as a standardized boat day. The concept of fishing effort is treated in more detail below.

Let y_t represent short-run yield:

$$y_t = qX_tE_t \tag{2.6}$$

where q is the catchability coefficient and E_t is fishing effort. The catchability coefficient is the embodiment of the technology that is used to harvest fish. Equation 2.6 is a standard equation for catch or yield that is often used in fisheries economics models. The fact that it is linear is very handy for computational purposes. The astute reader will have noticed, however, that it implicitly assumes that fisheries production does not obey the economic law of diminishing marginal productivity. Each additional unit of effort or stock size adds the same amount to catch. Also, if effort is high enough, the equation says that catch can be greater than the actual stock size. We look at other more realistic yield functions below, but for now, the tractability afforded by this formulation is very useful.

It is important to stress that this is a short-run production function. At any point in time, there is a given stock size. This function shows how much harvest will result for various levels of effort for a given stock size. The same amount of effort will produce more harvest when the stock size is higher and vice versa. This function, or its equivalent depending on the exact model in use, will be used to explain harvest in all that follows. The short-run nature of the function is perfectly applicable because industry participants make decisions in the context of the current stock, which may or may not be an equilibrium stock size.

However, while the yield from a given stock size for different levels of effort is important for understanding the current operation of a fishery, the concept of sustainable yield is also useful both for long-run analysis and because it can be used as a frame of reference. The sustainable yield curve shows the relationship between the level of fishing effort and the level of sustainable yield. A sustainable yield is one that can be maintained indefinitely because catch is equal to growth. The background and derivation of this function is discussed in detail in the exercises in the CD that accompany this chapter, and it can also be derived mathematically. To achieve a sustainable harvest, growth must equal short-run yield:

$$rX\left(1 - \frac{X}{K}\right) = qEX$$

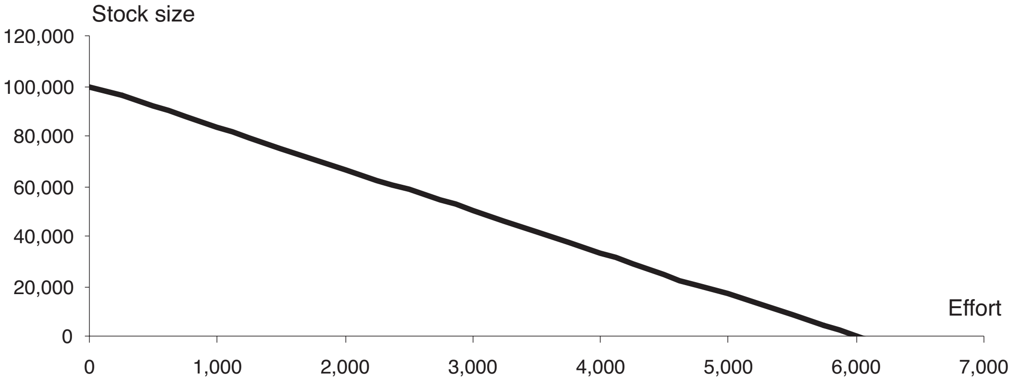


Figure 2.5 Population equilibrium curve.

or

$$r - \frac{rX}{K} = qE$$

Solving for X obtains:

$$X = K - \left(\frac{qK}{r}\right)E \tag{2.7}$$

This function, which is called the population equilibrium curve (PEC), is an important concept, and it is used many times both as an equation and in graphical form in the analysis to follow. It shows that equilibrium stock size will vary inversely with effort (see Figure 2.5, which shows a PEC using the parameters specified in Table 2.1.).

It was shown above that there will be a different equilibrium stock size for each level of effort. This is simply an extension of that principle. Each level of effort is associated with a level of harvest, and so over a particular range, each level of effort will be associated with an equilibrium stock size. In particular, when E equals zero, the equilibrium stock size is equal to K, the ecological carrying capacity. Increases in effort will decrease equilibrium stock size, and the sustainable stock size will be pushed to zero when E reaches r/q. The latter fact can be explained by substituting "r/q" for E in Equation 2.6. The resultant harvest is "rX," which is the rate of intrinsic growth in the Schaefer growth function. Harvest is canceling out stock growth and the stock will disappear.

Substituting the population equilibrium equation (Equation 2.7) into the short-run yield equation (Equation 2.6) produces an equation for the sustainable yield function as a function of E.

$$Y = aE - bE^2 \tag{2.8}$$

where $a = qK$ and $b = q^2K/r$. Stock size is obviously an important element in determining sustainable harvest, but it is subsumed in the equation because

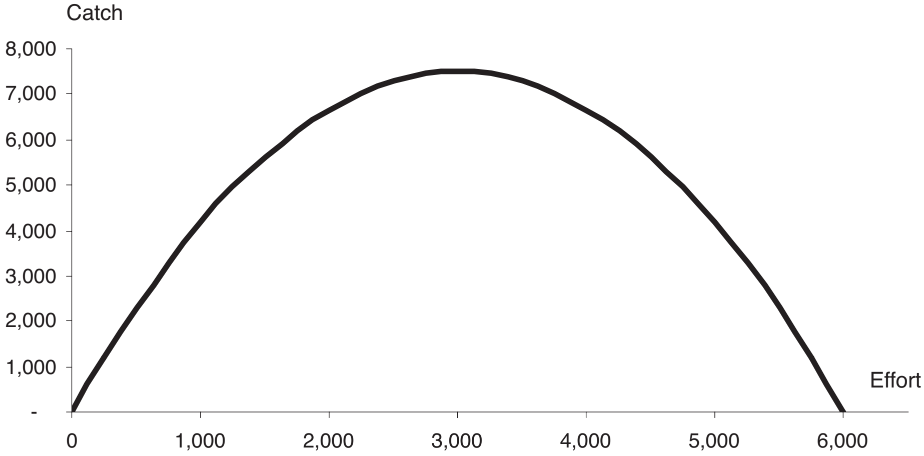


Figure 2.6 Sustainable yield curve.

equilibrium stock size is a function of effort. The shape of the sustainable yield curve depends on the parameters of the growth and short-run production equations, r, K, and q. Figure 2.6 shows the sustainable yield curve for our set of parameters. This curve shows the yield that will be produced for a given level of effort after the stock comes into equilibrium for that level of effort. At low levels of effort, increases in effort will increase sustainable yield, because growth increases with decreases in stock size in the right-hand side of the growth curve (see Figure 2.2). After a point, further increases in effort will decrease sustainable yield because further decreases in stock size will cause growth to fall. The maximum sustainable yield from a fishery is equal to the maximum growth from the stock.

The critical levels of E can be determined using Equation 2.8. Taking the derivative with respect to E, setting it equal to zero and solving for E, shows that E_{MSY} is equal to $a/2b$ or 3,000 days. It also follows that yield will fall to zero when $aE = bE^2$. This is where E equals a/b or 6,000 days.

The sustainable yield curve must be interpreted with great care. The normal interpretation of a graph is that it shows the relationship between values on the y-axis (the dependent variable) for different values on the x-axis (the independent variable). However, the sustainable yield curve shows the equilibrium level of harvest that will result from a given level of effort, *after the stock has reached equilibrium for that level of effort*. Both effort and stock are changing as you move along the curve.

Because the sustainable yield curve only considers equilibrium points, by its very nature, it ignores the time it takes for stock to adjust as effort and hence harvest are changed. Note that in the right-hand side of the curve, a literal interpretation of the curve says that a decrease in effort will increase harvest. However, a decrease in effort will always decrease harvest in the short run. The proper interpretation is that as effort is reduced, harvest will initially fall but will ultimately increase as stock size increases. Since the previous point on the curve was an equilibrium, harvest will be less than growth, and stock size will begin to grow. As it does, both harvest and growth will increase but growth will increase faster. The equilibrating factor that will bring the system to a new equilibrium back on the sustainable yield curve is the adjustment of stock until harvest is again equal to growth. This process is also explained in more detail in the exercises.

2.5 The basic bioeconomic model

Given the above-mentioned introduction to the biology of population dynamics, it is now possible to introduce economics into the analysis. The biological analysis allows for a discussion of the interactions between effort, harvest, and stock size. But in order to understand the operation of a commercial fishery, it is necessary to understand what level of effort will actually be produced under specified circumstances. This is the purpose of a bioeconomic model. Commercial fishing is an activity that is, for the most part, undertaken for profit. By introducing information on prices and costs and how the profit level will vary with output, it is possible to build a model that can help predict likely levels of effort and output. The one that is introduced here is very simple and is based on the sustainable yield curve. Despite its simplicity, it can be used to introduce the basic principles of fisheries bioeconomics. More rigorous models are introduced below to complete the story.

There are two fundamental questions at the heart of the bioeconomics of fisheries management. The first is: What level of effort should be produced? Implicit in this question is an explanation of whence comes the “should.” The second question is: What level of effort is likely to be produced by industry participants if left to their own devices? The importance of the questions flows from the fact that the answers to the two questions will be different. Explaining why they are different and what can be done to move a fishery toward the desired level of effort is an essential part of fisheries bioeconomics. The questions can be answered only in a static sense in this model, but it will suffice for present purposes. More detail is provided in terms of more complex but more realistic models below.

2.6 Deriving revenue and cost functions

To keep things simple, assume for the moment that both the price of fish, P, and the cost per unit of effort, C_E, are constants. Using these economic parameters, it is possible to derive “monetized” versions of the sustainable yield and the growth curves. They can be used to show how cost and revenue will vary with effort or stock size, respectively. Total sustainable revenue as a function of effort, TSR_E, can be represented as follows:

$$\mathrm{TSR}_E = P\left(aE - bE^2\right) \tag{2.9}$$

Remember from above that $a = qK$ and $b = q^2K/r$. Sustainable revenue is simply a linear transformation of the sustainable yield curve. It shows the amount of revenue that will be generated for any level of effort after the stock has adjusted to that effort. The TSR_E curve has the same shape as the sustainable yield curve, but while effort is still measured on the horizontal axis, the vertical axis is measured in terms of dollars rather than biomass.

Total cost as a function of effort, TC_E, can be expressed as follows:

$$\mathrm{TC}_E = C_E E \tag{2.10}$$

Total cost will increase linearly with effort.

The same information can be displayed in terms of average revenue and average costs. Average sustainable revenue of effort is simply total revenue divided by effort, and it is a decreasing function of E. Average cost of effort is total cost divided by effort and given the assumptions it is a horizontal straight line at C_E. Average cost of effort will be the same as marginal cost of effort.

$$\mathrm{ASR}_E = aP - bPE \tag{2.11}$$

$$\mathrm{AC}_E = C_E \tag{2.12}$$

To show the relationship between effort and stock size, it is also useful to look at sustainable revenue and cost in terms of stock size. Thinking of the problem in this context is also helpful for considering optimal utilization in a dynamic sense (see Chapter 3). Total sustainable revenue as a function of stock size, TSR_X, is simply the price of fish times the growth curve.

$$\mathrm{TSR}_X = PrX\left(1 - \frac{X}{K}\right) \tag{2.13}$$

It shows the revenue that can be obtained on a sustainable basis for any stock size. Using the PEC, Equation 2.7, it is possible to solve for the level of effort that will obtain the sustainable yield for any stock size.

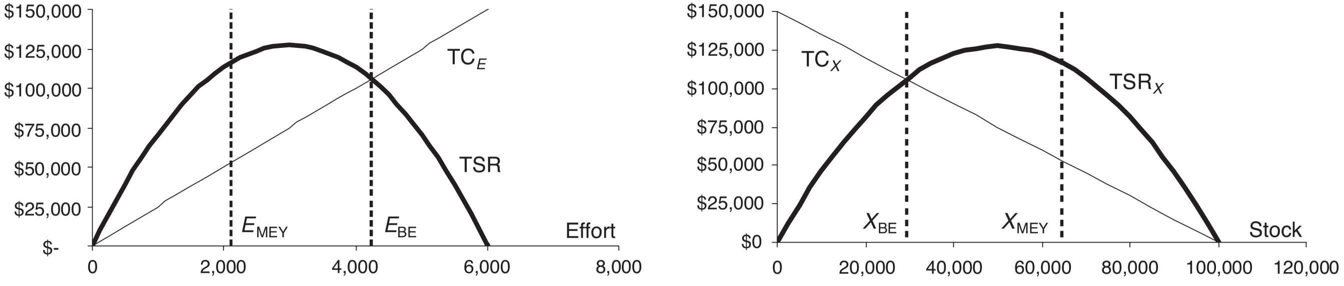
$$E = (K - X)\frac{r}{qK} \tag{2.14}$$

Therefore, the total cost of harvesting the sustainable yield from a given stock size, TC_X, can be expressed as follows:

$$\mathrm{TC}_X = C_E(K - X)\frac{r}{qK} \tag{2.15}$$

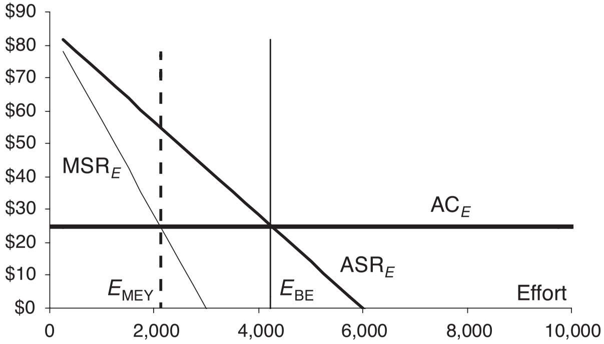
Because it takes less effort to produce the sustainable catch as stock size is increased, the TC_X has a negative slope with respect to stock size.

The total revenue and cost curves in terms of E and X are presented in Figures 2.7a and 2.7b. The average revenue and cost curves are presented in Figure 2.7c. The solution values for some critical variables are shown in the accompanying table.



(a)

(b)



(c)

E_{BE}	4,235	E_{MEY}	2,118
X_{BE}	29,412	X_{MEY}	64,706
Y_{BE}	6,228	Y_{MEY}	6,851
AC fish	$17	AC fish	$7.73
Profit	$0	Profit	$63,529

Figure 2.7 Total, average, and marginal revenues and costs.

2.7 Static maximum economic yield

The above-mentioned functions can be used to answer the two questions introduced above. Let us turn first to the question of how much effort should be produced. The answer, of course, depends on what one wishes to accomplish. While there are many possible objectives for managing a fishery, we concentrate on economic efficiency (see Chapter 1 and the literature cited there, however). As a contrast, note that one objective that is commonly proposed is the maximization of sustainable yield. It is not even necessary to consider economics to determine how to achieve that objective. Merely operate at the maximum point on the sustainable yield curve. In our example, this would call for annual effort equal to 3,000 days with a sustainable harvest of 7,500 tons.

The economically efficient level of output follows from basic economic principles. Economics is the study of the allocation of scarce resources. In terms of a fishery output, the objective is to maximize the net value of output. What is the fish worth to society and what has to be given up in order to harvest them? From this perspective, the question of how much effort should be produced turns on the relationship between what is gained and what is lost as more effort is applied to the fish stock. Fish that is put on the dock has value, but it does not get there for free. Inputs, which have other potential uses in the economy, are necessary to produce the effort used to catch fish. Taking all this into account, the optimal level of effort in a static sense is where the difference between sustainable revenue and the cost curves is maximized (see Figures 2.7a and 2.7b). This occurs at E_{MEY} and X_{MEY}.

More formally, the static maximum economic yield occurs at that level of E where total sustainable net returns are maximized. Total net returns can be expressed as follows:

$$\mathrm{NR}_E = P(aE - bE^2) - C_E E \tag{2.16}$$

The first derivative of NR_E is:

$$\frac{\partial \, \mathrm{NR}_E}{\partial E} = P(a - 2bE) - C_E \tag{2.17}$$

NR_E will be maximized at the level of effort where this equation is equal to zero, which can be expressed as follows:

$$P(a - 2bE) = C_E \tag{2.18}$$

The left-hand side can be interpreted as the marginal sustainable revenue of effort. It is the change in value of output, which results from a change in effort. The right-hand side is the marginal cost per unit of effort. The interpretation is that it makes sense to increase the production of effort as long as the value of the extra harvest is greater than the cost of taking that harvest. Solving

Equation 2.18 for E obtains:

$$E_{\mathrm{MEY}} = \frac{Pa - C_E}{2Pb} \tag{2.19}$$

In our example, E_{MEY} equals 2118 units of effort.

The static economic optimum can also be pictured in terms of revenue and cost as a function of stock size (see Figure 2.7b). The profit maximum occurs at a stock size of 64,706, which is the equilibrium stock size when effort is equal to 2118.

Because of its fundamental importance in understanding the logic of optimal utilization from an economic point of view, it will be useful to restate the economic interpretation of the above mathematics. Because this book is also written for noneconomists, it is very important to make clear that the issue is more than just maximizing the net value of harvest. Economists are not concerned with maximizing net returns just for the sake of profits. The concern is with the optimal balance of production in the fishery and the rest of the economy. The necessary condition for maximizing net returns is stated in Equation 2.18, which states that MR_E must equal MC_E. In terms of Figure 2.7b, the optimal level of effort occurs at the intersection of the MR_E and the MC_E curves. MR_E is the value of the extra output that is produced in the long run for each unit increase in effort. MC_E is the increase in cost for producing that extra unit of effort. From an economy-wide perspective, this also represents the value of goods and services that could have been produced had the inputs used to produce effort were used elsewhere in the economy. As long as the value of the extra fish is greater than the opportunity cost of producing it, it makes sense to continue allocating effort to the fishery. The revenue of the industry will go up faster than cost and so total profits will increase. From society's perspective, the value of fish production will go up more than the value of output elsewhere in the economy will go down because of the resources that are used to produce effort. When MR_E is less than MC_E, it is costing more to produce the effort than that value of fishery output that is produced. It does not make sense to produce fishing effort in this range. The optimal level of effort is where MR_E is equal to MC_E.

2.8 Open access utilization of a fishery

Let us now turn to the question of where a commercial fishery will tend to operate given the private motivations of individual participants. A basic tenet of the economic analysis of individual business firm behavior is that profit maximization is the primary goal of business operation and decisions with respect to entry to or exit from an industry or on the level annual output are made on the basis of furthering this goal. Adam Smith called this search for profits the "invisible hand" because it helps to move resources to their highest valued uses. But the invisible hand will not work when individuals are not responsible for the full costs of their behavior. An important element in the open access operation of a fishery is that each participant will have incentives to make his or her independent decisions based on private returns. The effects of these independent decisions have important interdependent consequences on all participants.

The motivations for individual actions can best be explained in terms of this model, using Figure 2.7c. We present a more detailed discussion below. Assuming similar participants, the average revenues and costs of the fishery as a whole show what is happening at the individual firm level. Although effort is measured as a continuum on the horizontal axis, it is important to realize that decisions to produce effort are made by separate individuals. If each participant uses individual revenue and cost as the basis for making those decisions, the fishery will end up at a bioeconomic equilibrium at the intersection of the ASR_E and the AC_E curves (see Equations 2.11 and 2.12). Therefore, the bioeconomic equilibrium level of effort is:

$$E_{\mathrm{BE}} = \frac{aP - C_E}{bP} \tag{2.20}$$

The logic of this equilibrium can be explained as follows. Anywhere to the left-hand side of E_{BE} in Figure 2.7c, the revenue per unit of effort is greater than the cost per unit of effort. On an individual basis, all the existing participants will be making profits. There will be incentives to produce more effort. Further, potential participants can see that the average net earnings of existing participants are such that it may be worthwhile to join the fishery. These incentives will encourage individuals to increase their effort even when total sustainable catch will fall. Note that after effort gets larger than 3,000, average revenue will still be higher than average cost, but sustainable yield and revenue will be decreasing.

By the same token, at levels of effort greater than E_{BE} average returns will be less than costs and individual producers will have incentives to reduce effort and perhaps to exit the fishery. Because effort will increase to the left of E_{BE} and decrease to the right of it, there will be an equilibrium at this point.

The bioeconomic equilibrium is also depicted in Figures 2.7a and 2.7b. It occurs at the intersection of the total revenue and total cost curves in each case. This shows very clearly that all possible net gains will be dissipated in an open access fishery.

The policy-relevant point is that open access utilization of a fishery will not lead to an economically efficient outcome. The equilibrium amount of effort will be higher than necessary, and it will lead to a lower equilibrium stock size than is appropriate.

Note from the table accompanying Figure 2.7 that the average cost of a unit of fish (as calculated by dividing output by total harvest costs) is lower at the static maximum economic yield point than it is at the bioeconomic equilibrium. Because entry will continue under open access as long as there are positive returns, effort will increase until the combination of effort and stock size is such that the average cost of fish is equal to the price of fish. It is important to realize that both effort and the stock are inputs in production. At the maximum economic yield point, the combination of effort and stock size is such that the average cost of fish will be at a level where profits are maximized.

The obvious question is why an open access fishery will tend to produce an inefficient level of effort where net returns are not maximized. The answer lies in the incentives provided by the structure of the property rights. While the individual operators own their own boats and therefore have property rights in the man-made capital in the fishery, none can claim ownership of the fish in the sea. There are no property rights to the living capital of the fishery. While each participant may be better off if their boat could be working in combination with a higher fish stock, no one operator can do anything that will guarantee that investments in the stock will pay off. If an operator reduces effort to allow stock size to grow, there is no guarantee that others will not come in and take the extra fish. Given this situation, individual operators tend to only consider the difference between the average returns per unit of effort and the individual cost of producing a unit of effort. That is, individual operators will consider the difference between AR_E and MC_E, not the difference between MR_E and MC_E. MR_E measures the increase in the value of output to the fishery as a whole, but individual operators are only concerned with the returns they will receive. As can be seen from Figure 2.7c, MR_E will be less than MC_E over the range where AR_E is greater than MC_E. In that range, individual operators will have incentives to increase effort because the private gains are positive even though the gains for the fishery as a whole are negative. While each individual is operating rationally according to private net returns, acting in concert, they produce a result where net returns are pushed to zero.

To understand the importance of property rights, consider the hypothetical case where a single individual or an organized group of individuals has a de facto property right to the fish stock that allows them to control access to the fishery. The amount of effort that would be introduced would be a unified central decision rather than the result of the independent decisions of many private individuals. Since the full benefits and costs of introducing an extra unit of effort into the fishery would be borne by the decision makers, if they are concerned about total net returns, they will follow the MR_E equal MC_E rule. Property rights determine where the decisions are made, and this can make all the difference. In the ideal world, it is important to get the property rights at a level where the decision maker bears all benefits and all the costs. This is not the case in an open access fishery where the effects of the decision to increase effort are felt by all participants, not just by the individual decision maker.

This analysis needs to be interpreted with care, however. The key premise is that operators act independently. If operators understand what is happening, and can agree to operating rules where each individual takes the effects of others into account, the waste of open access can be corrected. For example, if they can see that total returns to all participants will be reduced if effort is increased beyond E_{MEY}, they can set limits on what each will produce and make arrangements to share the returns. While this is a theoretical possibility, it does not occur in many real-world situations because the number of possible participants is so large that it is hard for any of them to see the effect they are having on others, and more importantly, it is very difficult to reach an enforceable agreement to keep effort to the appropriate level.

We see below however that fisheries regulations which attempt to mimic the incentives provided by ownership of the fish stock can be very successful in obtaining both the higher sustainable fish stocks matched with an efficient level of effort. The rights-based management schemes prevent the dissipation of net returns that occurs in an open access fishery and, as shown below, in fisheries that are regulated by non-rights-based programs.

2.9 Postscript on structural change under open access

The above-mentioned analysis has shown the fundamental problem with an open access fishery. Because of the lack of property rights, there will be incentives for private individuals acting in their own interest to overfish the stock. Too many inputs will be allocated to the fishery in the sense that the marginal benefit for the last units will be less than the marginal cost. As a result, the stock size will be lower than it should and potential returns will be dissipated. These results were demonstrated in a static model where it was assumed that prices, cost, and technology remained constant. The forecast for open access fisheries utilization is even bleaker when, as has happened in the past, there are increases in the price of fish or improvements in harvesting technology. Anything which lowers the cost of inputs associated with the production of effort will also have deleterious long-term effects.

As a frame of reference for this discussion, note in the markets for most other goods and services, higher prices, lower input cost, or improvements in technology will be advantageous because they will bring forth increased production. These changes increase profits, which create incentives to bring more inputs to the industry. The result will be more output. The critical point however is that in other industries it is possible to add more of *all* the necessary inputs. This is not the case with fisheries. While it is possible to bring in more boats, it is not possible to add more productive capacity in the form of a larger fish stock. This crucial difference will produce different results.

Consider Figure 2.8, which shows the effect of an increase in price from the status quo situation described above. The total sustainable revenue curve (TSR_E) will shift up by a proportionate amount at every level of effort. The TSR_E will intersect the total cost curve (TC_E) at a higher level of effort. The increased profits will attract more effort, but in this case the result will be a reduction in stock size and harvest level. The fact that equilibrium stock size will fall should come as no surprise. This follows directly from the concept of the PEC, which shows the inverse relationship between equilibrium stock size and effort (see Figure 2.5). Equilibrium catch falls because the status quo is in the negatively sloped portion of the TSR_E curve.

The results are somewhat different if the TC_E curve intersects the TSR_E curve in its upward sloping portion. In this case it is possible for an increase in price to bring forth an increase in output even though the equilibrium stock size will

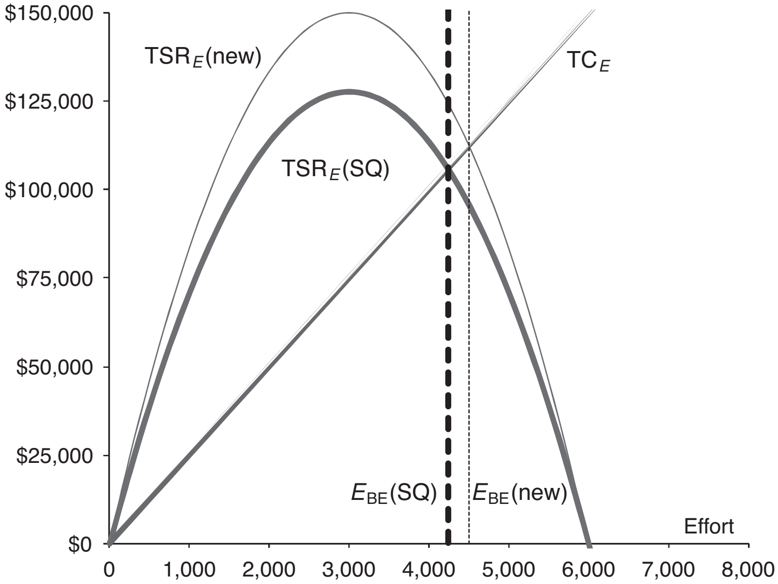


Figure 2.8 Price effect on bioeconomic equilibrium.

fall. But since net returns are zero in the status quo situation and at the new equilibrium, there is no gain. The possible advantages of the increased price are dissipated through the increase in effort and decrease in stock.

The same general results follow where there is a reduction in the cost of effort or an improvement in technology such that the catchability coefficient (q) increases. The potential beneficial effects of these improvements are dissipated under open access. These two cases are discussed in the exercises for this chapter.

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Chapter 3

Open access dynamics

3.1 Introduction

The purpose of this chapter is twofold. The first is to more formally introduce the concept of fishery dynamics which shows the analysis of how stock and effort change over time in response to biological and economic conditions. The second is to introduce a disaggregated model in order to consider the decision-making process of individual vessel operators. This disaggregated model provides a more robust picture of the exploitation of a fishery. It is especially important when considering the effects of regulation.

First, we describe the fundamentals of fishery dynamics in terms of the aggregate model used in Chapter 2. Second, we develop the disaggregated model designing it such that the results are comparable to that of the aggregate model. We then demonstrate how the dynamic analysis will change when using the disaggregated model. In the process, we provide a detailed description of individual and group action in a fishery looking at such issues as when to put a vessel into a fishery, when to pull it out, and how to operate it under different stock conditions.

3.2 Bioeconomic equilibrium

A fishery will achieve an open access economic equilibrium when total revenue equals total cost. The analytical analysis above was in terms of the sustainable yield curve which subsumed the effects of effort on stock size. The goal was to explain the differences between the optimal utilization of a fishery and the open access equilibrium. Let’s broaden the discussion and consider the concept of a bioeconomic equilibrium. The discussion here will focus on the process of obtaining the equilibrium, and equal attention will be given to both the economic and biological aspects of a fishery. The discussion is important because a fishery is very seldom, if ever, in a state of equilibrium. The concept of an equilibrium is useful for looking at the big picture, but not very useful when considering practical policy. At any point in time, there will be a given stock size and a certain amount of potential effort. More than likely, it will not be the equilibrium combination. For reasons that will be explained below, stock and effort will be changing over time. When thinking about regulation, it is necessary to know more than just the status quo condition. It is necessary to know where the fishery is headed. Just as important it is necessary to know how to change the time-path trajectory so that it will head in the desired direction.

A bioeconomic equilibrium occurs when there is no change in either stock size or the level of effort. It is a simultaneous biological and economic equilibrium. Recall that the population equilibrium curve (PEC) (Equation 2.7) shows the combinations of stock and effort where there will be a biological equilibrium. The PEC for our set of parameters is pictured in Figure 3.1. For any stock size, it shows the level of effort where catch equals growth. Because catch is equal to growth, the stock size will not change. Alternatively, the PEC can be seen as a line that divides the stock-effort space into combinations of effort and stock size where stock will increase or decrease. At all points above the line, the catch for the existing level of effort will be greater than growth for the existing stock size, and so stock size will fall. Alternatively, at all combinations of effort and stock size below the line, catch will be less than growth, and so stock size will grow. The bioeconomic equilibrium will have to take place somewhere along the PEC.

An economic equilibrium occurs where there is no tendency for fishing effort to change. This condition will occur when the revenue from harvest is equal to the cost of the effort necessary to produce that harvest. Whenever the existing combination of effort and stock is such that total revenue is greater than total cost, there will be incentives for current participants to produce more effort and for others to obtain the means to produce effort and join the fishery. This is explained in more detail in the disaggregated model. On the other hand, when the existing combination of stock and effort produces the reverse situation, there will be incentives for effort to decrease.

Using the short-run yield function (Equation 2.6), the condition for an economic equilibrium (total revenue equals total cost) can be expressed as:

$$PqXE = C_E E \tag{3.1}$$

We do not want to use the sustainable yield curve because it subsumes a biological equilibrium. Solving for X produces:

$$X = \frac{C_E}{Pq} \tag{3.2}$$

This expression can be called the economic equilibrium curve (EEC), and it shows the combinations of X and E, where revenues will equal cost. Given the linear yield function, the stock size that generates zero profits is independent of the level of effort, and so the EEC is a horizontal line. (As will be shown below, with more general assumptions the EEC can have different slopes.) The EEC is also pictured in Figure 3.1. It can be seen as a line that divides the stock-effort space into sections where profits will be positive or negative. At points above the EEC, the combinations of *E* and *X* will generate revenues that are greater than costs. In these situations, effort will tend to increase. On the other hand, at points below the curve, the combinations of *X* and *E* will generate revenues that are less than costs. In these situations, effort will tend to decrease.

The PEC and the EEC will intersect at the bioeconomic equilibrium combination of *X* and *E*. All points on the PEC represent biological equilibria, and all points on the EEC represent economic equilibria. Therefore, their intersection occurs at a combination of *X* and *E* that is both a biological and an economic equilibria. Using the EEC and the PEC provides an alternative method of looking at the open access equilibrium. But in this case, the important variables are pictured in the same graph. The equilibrium levels of effort and stock size are the same as pictured in Figure 2.7.

To anticipate the discussion of the dynamics of achieving a bioeconomic equilibrium, it follows from the above that the EEC and the PEC divide the stock-effort space into four areas. These areas and the direction of change in *E* and *X* can be summarized as follows:

Area above PEC and above EEC	*X* decreases and *E* increases
Area above PEC and below EEC	*X* decreases and *E* decreases
Area below PEC and below EEC	*X* increases and *E* decreases
Area below PEC and above EEC	*X* increases and *E* increases

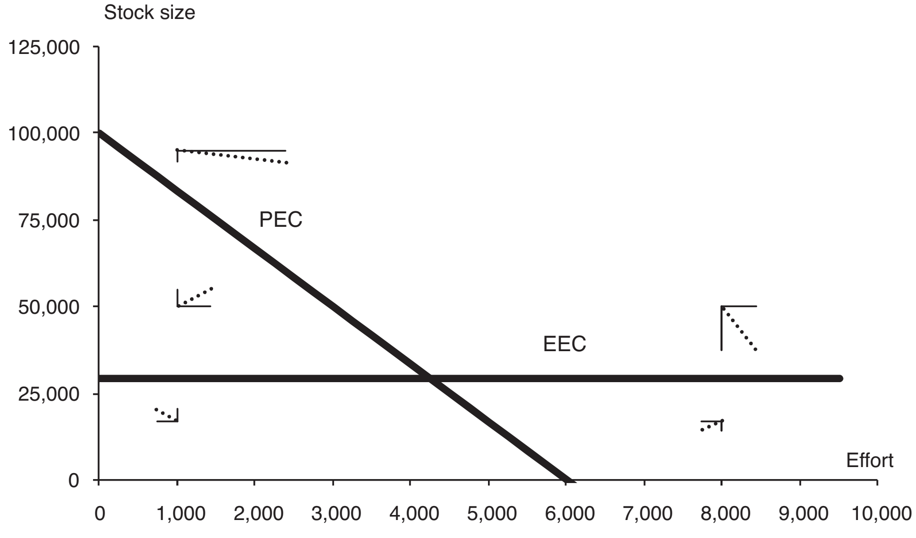

Figure 3.1 PEC and EEC in stock-effort space.

Starting from a virgin biomass and a low level of effort, these vectors of change will set a pattern of overall change that will generally set a clockwise path around the bioeconomic equilibrium combination of X and E. Whether the path will actually lead to the equilibrium depends on the relative rates of change of E and X. This is discussed in more detail below as well as in the exercises given in the CD.

3.3 The process of obtaining an equilibrium

In order to understand the operation of an open access fishery, it is necessary to consider the process through which a fishery achieves a bioeconomic equilibrium. That is, how will stock size and the amount of effort change through time when the fishery is not in a bioeconomic equilibrium. This is a topic that was first investigated by Vernon Smith (1968, 1969). The change in stock size in any period is the difference between catch and growth for the status quo level of effort and stock size. Using the growth and the short-run yield functions, the discrete function for the change in stock size can be expressed as follows:

$$X_{t+1} = X_t + r X_t \left(1 - \frac{X_t}{K}\right) - q X_t E_t \tag{3.3}$$

The change in stock size follows directly from the basic logic of population dynamics. There is nothing quite so pure for calculating the change in effort over time. However, it makes sense to posit that the change in effort will be proportional to the net returns per unit of effort. This can be expressed as follows:

$$E_{t+1} = E_t + \frac{\varphi\,[P q X_t E_t - C_E E_t]}{E_t}$$

or

$$E_{t+1} = E_t + \varphi\,[P q X_t - C_E] \tag{3.4}$$

The rate of proportionality, φ, is called the entry/exit coefficient. If the net returns per unit of effort are positive, effort will increase. If the net returns per unit of effort are negative, effort will decrease. For the purposes of discussion here, the value of φ has been set to 25; see Table 3.1.

Recall that the PEC and the EEC divide the stock-effort space into four areas in which there will be particular types of changes in both stock size and the level of effort. Given a status quo combination of stock size and effort, the above equations allow for the calculation of the exact amount of change in each. Combining these two changes will provide the overall vector of change in stock-effort space. This is demonstrated at five different points in Figure 3.1. In each case, the black lines show the direction of the change in effort and stock for the given set of parameters. The dotted lines show the resultant vectors of change. Of particular interest is the fact that not only does the direction of the vector change at different points on the graph, but so does the length of the vector. For a given level of effort, as stock size is increased from zero toward the EEC, the change in effort starts out as a relatively large movement toward the left but gradually changes to a smaller leftward movement. At the EEC, there is no change in effort. As effort is increased upward from the EEC, there is an ever-increasing rightward movement of effort. Similarly, for any particular stock size, as effort is increased toward the PEC, there is a smaller and smaller upward change in stock size. There is no change in stock size on the PEC. As effort is increased to the right of the PEC, there will be larger and larger downward changes in stock size. Put differently, the angle and the length of the vector of change will vary according to the location of the initial point. When approaching the PEC, the change in stock size moves toward zero. When approaching the EEC, the change in effort moves toward zero.

The accumulated effects of these changes over time can be demonstrated in Figure 3.2. The dotted line in Figure 3.2a shows the trajectory of stock and effort, assuming an initial point with a small fleet size and a virgin stock. It must be emphasized that the shape of the curve depends on the absolute and relative values of the system parameters. The current parameters have been selected because they produce a certain pattern of adjustment that is useful for explaining some basic points. However, an important part of the analysis will be to explain how changes in the parameters can change the pattern of adjustment. It is also important to bear in mind that some aspects of time cannot be fully explained when interpreting the trajectory curve. As demonstrated by the lengths of the vectors in Figure 3.1, the system is moving faster along those parts of the trajectory where stock size and effort are high.

The trajectory curve shows one possible way in which a newly developed fishery can approach an equilibrium. Note that the slope of the path coincides with the preceding discussion. The curve starts out above the EEC, and to the right of the PEC the path will move in a southeast direction. Stock size will increase and effort will increase. In a new fishery with a virgin stock and low levels of effort, profits can be high that will attract more effort, which will tend to decrease stock size. When the trajectory crosses over the EEC curve, the path will change and move to the southwest. Effort and stock will both fall. Eventually, a point is reached where profits become negative and effort starts to decrease. However, since catch is still greater than growth, stock size continues to fall. When the path crosses the PEC curve, it will change again and move in a northwest direction. The decrease in effort has reduced catch to the point where stock size starts to increase. However, stock size is not high enough to generate positive profits, and so effort still decreases. When the path crosses the EEC again, the path will start to move in a northeast direction. The stock size has increased enough that profits are positive, and so effort starts to increase again. However, effort is still low enough that catch is less than growth and the stock size will still be increasing. When the path crosses the PEC again, it is back in the situation it started in and will move in a southeast direction. As pictured in Figure 3.2a, the path keeps spiraling inward toward the bioeconomic equilibrium combination of effort and stock size.

This analysis specifically demonstrates one of the problems of using a static model to understand a fishery. The static model shows the combination of effort and stock size where the fishery reaches an equilibrium. However, as can be seen from the trajectory that, the stock size is pushed lower and the level of effort will be pushed higher than these equilibrium levels. This can be called the *dynamic overshoot*. Things can be worse and that is demonstrated in the static model.

Figures 3.2b and 3.2c provide a slightly different perspective. Figure 3.2b shows the sustainable revenue and cost curve as a function of effort. Superimposed on this is the path of effort and total revenue earned as the fishery follows the time path of effort and stock size shown in Figure 3.2a. The sustainable revenue curve shows the revenue that will be generated after the stock comes into equilibrium for a given level of effort. The dotted line shows the revenue that is generated for each level of effort produced in the history of the fishery, given the stock size that exists at that point in time. Note that as the fishery first expands, the level of revenue for each level of effort is above the cost of producing it and effort expands. This is the highest upward sloping portion of the time path. After a while, however, the revenue produced falls because of the reduction in stock size (not shown in the graph) and effort will start to fall. Effort will continue to fall as long as revenue is less than cost. This is the second portion of the time path which moves in a southwest direction. The equilibrium level of effort is where the level of revenue that is achieved on the time path matches the sustainable revenue for that level of effort and is also equal to the total cost at that point.

Figure 3.2c shows total revenue and cost curves in terms of stock size. Superimposed on this is the path of stock size and total revenue earned as the fishery follows the time path of stock size and effort shown in Figure 3.2a. In this case, the path starts at the right-hand side of the graph and moves to the northwest. Initially, actual revenue, represented by the dotted line, is above sustainable revenue. This means that given the harvest level produced by the existing level of effort, which is not shown on this curve, catch is above growth and the stock size falls. As the combination of stock size and effort change, eventually a point is reached where actual revenue is less than sustainable revenue, which means catch is less than growth and stock size will increase. The equilibrium stock size is achieved when the actual revenue equals the sustainable revenue and the cost it takes to produce the actual level of harvest.

The remaining graphs in the figure show how important variables change through time. Given the initial virgin stock size, in this particular case, the overall changes will cause stock size to undulate up and down until it settles at the equilibrium level (see Figure 3.2d). Given the changes in stock size and effort, growth and harvest will change as shown in Figure 3.2f. Note that in those periods where growth is greater than catch, stock size will increase, and vice versa. The driving force behind changes in effort is demonstrated in Figures 3.2e and 3.2g. Whenever net returns are positive, the fleet size will increase and vice versa. Again, in this case, the level of effort will undulate up and down and

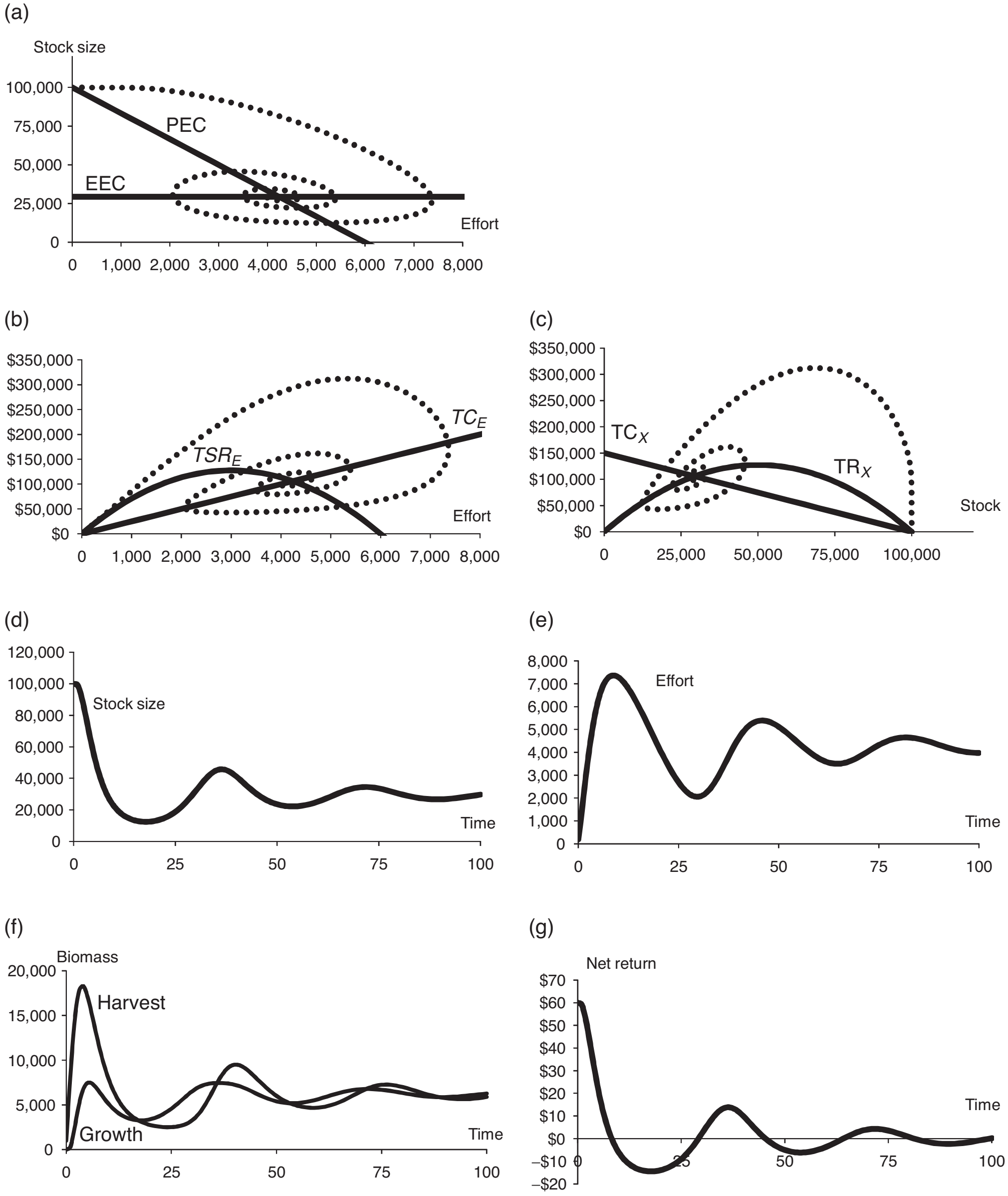

Figure 3.2 Static and dynamic biomass, yield, costs, and revenues.

eventually will settle at the equilibrium level. Notice that the entry of effort will always push the net return to effort to zero.

One might be tempted to try to correlate the changes in catch to the changes in effort, but they do not always move in the same direction because stock size is changing at the same time. Therefore, effort may be increasing, but catch may fall if stock size is decreasing fast enough.

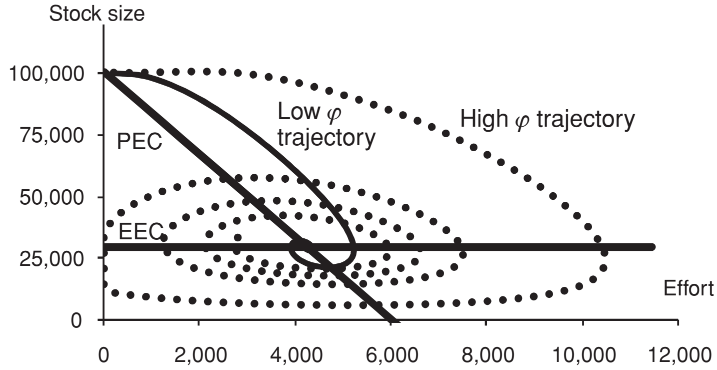

Figure 3.3 Dynamic trajectory paths of stock and fleet size toward the bioeconomic equilibrium.

Again, it should be remembered that the above time paths are the result of the absolute and relative sizes of the economic and biological parameters. The trajectory is one that many commercial fisheries around the world have followed. However, changes in any of the parameters, except the entry/exit coefficient, will change the bioeconomic equilibrium point, and changes in all of them will change the time paths and some can affect the stability of the system.

In order to get a better picture of what is driving things, let's briefly consider how changes in different parameters will change things. The effect of different entry/exit coefficients can be demonstrated using Figure 3.3. The solid trajectory line represents the time path when φ is reduced from 25 to 10. With this reduced rate, the fishery approaches the bioeconomic equilibrium much more directly. The entry of vessels is small relative to the decrease in stock size and the dynamic overshoot is less pronounced.

At the other extreme, the dotted trajectory represents the case when φ is increased to 50. There is a large loop where effort is pushed to zero when the stock is reduced to a very low level. Because there is no catch, the stock then begins to grow, and when it gets above the bioeconomic equilibrium level, effort will start to enter the fishery again. However, from that point on, the time path goes in to a continuous cycle and the bioeconomic equilibrium is never reached.

A crucial area is the portion below the EEC and to the right of the PEC. In that area, the stock size is low and still decreasing while effort is relatively high but also decreasing. At the extreme, if effort does not fall fast enough, theoretically the stock could be pushed to zero. This is an artifact of the assumptions of this simple model. The more realistic disaggregated model discussed below has different results and for very good reasons.

Other changes in parameter values will produce different trajectories. This will be explored in some detail in the exercises given in the CD. Without going into the graphical details here, it will be useful to discuss several important points. First, while the above shows how a change in φ will affect the trajectory, it is actually the ratio of φ to r (the intrinsic rate of growth) that is critical. Stocks with a higher r have a better ability to reproduce and to withstand the pressure of commercial fishing. Using the cyclical trajectory in Figure 3.3 as a frame of reference, an increase in r will rotate the PEC to the right, which will increase the bioeconomic equilibrium level of effort. At the same time, the time path will become less cyclical and the chance of reaching an equilibrium increases. Even with the higher level of φ, the higher r means that it is possible to reach an equilibrium. The relationship between the relative size of φ and r and the shape of the trajectory can be summarized as follows. For a constant r, increases in φ will tend to make the path more cylindrical; however, for a constant φ, increases in r will make it less cylindrical. Put another way, as the ratio of φ to r increases, the path will become more cylindrical.

Anything that increases profit, such as an increase in P or q, or a decrease in C_E, will tend to make the trajectory more cylindrical and reduce the chance of achieving an equilibrium or at least increase the time it will take to achieve one. Also note that the initial conditions can have significant effects on the time path and on the potential for a stable equilibrium. This can be better demonstrated in some of the more realistic models that will be discussed below.

3.4 Bioeconomic equilibrium in a disaggregated model

The aggregate model of Chapter 2 is useful for demonstrating the general conclusions of open access fisheries utilization. The decision-making process dealing with the actual production of effort is glossed over in order to focus on the basic elements of the analysis. To provide for a more complete analysis, we will now develop a disaggregated model which takes into account the number and activities of the vessels which actually produce the effort. The number of operating vessels, V, will be the primary control variable in the model, but it is also necessary to consider how the vessels determine how much effort to produce.

To gain an appreciation of the many dimensions that are involved, the model will explicitly consider how different elements can be used to produce effort. While our model only considers two variables, in the real world there are many variable inputs that go into the operation of a vessel, and the vessel operator will have incentives to choose that combination which maximizes profit. This is important because, as will be shown below, traditional fisheries regulation, directly or indirectly, affects the choice of inputs, and hence the efficiency and profitability of vessels.

The disaggregated model is analogous to the standard microeconomic analysis of firm that uses marginal and average cost curves to explain profit-maximizing behavior. However, because season closures, total allowable harvest limits, trip limits, and other common types of regulation can affect the number of days a vessel can operate, it is necessary to add an extra dimension and explicitly add days of production into the analysis.

One goal here is to organize the disaggregate model such that it is directly comparable to the aggregate model. We will continue to use the same biological and technological parameters as above. The comparability with respect to cost will be discussed below. Table 3.1 provides a summary of the values that will be used for the new parameters, which will be introduced below.

Table 3.1 Parameter set for the disaggregated model

	Symbol	**Value**
Biological parameters		
Intrinsic growth rate	r	0.3
Carrying capacity	K	100,000
Initial stock size	X_{initial}	100,000
Equilibrium values		
Maximum sustainable yield	Y_{MSY}	7,500
Bioeconomic equilibrium yield	Y_{BE}	6,228
Maximum economic yield	Y_{MEY}	6,851
Stock at MSY	X_{MSY}	50,000
Stock at BE	X_{BE}	29,412
Stock at MEY	X_{MEY}	64,706
Vessels at MSY	V_{MSY}	10.00
Effort at MSY	E_{MSY}	3,000
Vessels at BE	V_{BE}	14.12
Effort at BE	E_{BE}	4,235
Vessels at MEY	V_{MEY}	7.06
Effort at MEY	E_{MEY}	2,118
Economic parameters		
Price of fish	P	\$17.00
Catchability coefficient	q	0.000050
Cost parameters		
Vertical intercept of daily mc	C_i	\$5.00
Slope of daily mc	C_s	\$5.00
Fixed cost	FC_{b}	\$3,000
Maximum days fished	$D_{\max}$	150
Maximum daily effort	Max f	3.20
Entry/exit coefficent	φ'	0.00028
Aggregate entry/exit coefficient	φ	25
Initial fleet size	V_{initial}	1
Calculated economic parameters		
Daily effort at minimum ATC	$f_{\min}$	2.00
Annual effort at minimum ATC	$D_{\max}f_{\min}$	300
Annual variable cost at minimum ATC	$VC_{\min}$	\$4,500
Cost per unit effort at minimum ATC	C_E^*	\$25.00

It should be emphasized that the model is constructed to capture the basic nature of the issues involved rather than to provide a complete picture of actual vessel operation. Even with this simplicity, the model does provide useful insights into fishery operation and it also provides a basis for explaining the effects of regulation.

The amount of aggregate effort produced by a fleet can be viewed as a function of the number of vessels (V), the number of days fished (D), and the amount of effort produced per day (f). Uppercase E is commonly used to denote aggregate effort in fisheries economics models. We have followed that usage in our analysis. While lowercase e may appear as a logical choice for vessel daily effort, this could cause confusion because natural (base e) logarithms must be used in the age-class models developed below. Therefore, lowercase f is used for vessel level daily effort.

Our aggregate model will be based on these three variables. To simplify the mathematical analysis, we can, without loss of generality, assume that the normal number of days fished is a constant based on tradition, seasonality, weather patterns, the need to perform maintenance on the vessels, or some combination of these effects. This will avoid the necessity of making D an endogenous variable but will still allow for a consideration of regulations which directly or indirectly control the season length. Let $D_{\max}$ represent the constant number of days normally fished. Daily effort, f, will be an endogenous variable. In order to take the realities of actual vessel operation into account, let max f represent the maximum amount of effort that can be produced on any given day.

The relationship between the amount of effort produced in the aggregate and disaggregate models can be expressed as follows:

$$E = V f D_{\max} \tag{3.5}$$

Because actual production decisions are taken at the vessel level, the vessel cost function will be the basic building block of the fleet cost function. Given the constant $D_{\max}$, the annual vessel production of effort will be a function of f. That is, $E_v = D_{\max} f$. Assuming that cost is a quadratic function of f, the vessel total cost of effort function can be expressed as follows:

$$C_v(E_v) = D_{\max}\left[c_i f + c_s f^2\right] + \mathrm{FC} \tag{3.6}$$

where c_i and c_s are parameters and FC is the annual fixed cost. The vessel seasonal average cost (the average cost of a single unit of effort) is:

$$AC_v(D_{\max} f) = c_i + c_s f + \frac{\mathrm{FC}}{[f D_{\max}]} \tag{3.7}$$

Since effort is produced on a daily basis, the marginal cost of a single unit of effort is:

$$\mathrm{MC}(f) = c_i + 2c_s f \tag{3.8}$$

The vessel will be operating at the minimum of its average cost curve when average cost is equal to marginal cost. Setting Equations 3.7 and 3.8 equal and solving for f will give this level of f, call it $f_{\min}$.

$$f_{\min} = \left[\frac{\mathrm{FC}}{D_{\max} c_s}\right]^{1/2} \tag{3.9}$$

This will be a useful reference point for our analysis because it means that if a boat operates at $f_{\min}$ each fishing day, the average cost of effort at the vessel level will be minimized. (It is assumed that max f is greater than $f_{\min}$.) Let C^*_E be the cost per unit of effort of operating at $f_{\min}$.

$$C^*_E = c_i + c_s f_{\min} + \frac{\mathrm{FC}}{[f_{\min} D_{\max}]} \tag{3.10}$$

The cost parameters in Table 3.1 have been chosen such that C^*_E equal C_E in the aggregate model. This allows for an easy comparison between the two models because the equilibrium stock and fleet sizes will be the same. To be precise, given the parameters in the table, the value of $f_{\min}$ is 2, and with that the value of C^*_E is \$25. While the equilibrium values will be the same, see below, the process of reaching the equilibrium will be different, but that is the point of the story.

Using the above cost constructs, it is possible to expand the analysis of the previous chapter. First, it is possible to use vessel cost curves to look at decision making at the vessel level, which provides insights into microlevel bioeconomics and provides a more complete picture of how the cost of effort is determined. Second, the simple one-dimensional model of optimal and open access utilization can be made multidimensional to provide a more complete explanation of the details of economic efficiency. In addition, the dynamic analysis developed in the first part of this chapter can be expanded to look at the entry and exit of vessels, which also provides a better picture of open access utilization.

3.4.1 Vessel operation

Turning to the first issue, the primary vessel control variable is the amount of effort to produce per day. The vessel profit function is:

$$\pi_{v(t)} = D_{\max}\pi_D - \mathrm{FC} \tag{3.11a}$$

where π_D, the daily profit function, is:

$$\pi_D = PfqX - \left[c_i f + c_s f^2\right] \tag{3.11b}$$

The latter is the basis for determining the optimum daily level of effort. The profit-maximizing level of f will occur where the marginal return to effort is equal to the marginal cost of effort.

$$PqX = c_i + 2c_s f \tag{3.12}$$

Therefore the profit maximizing level of daily effort, f, is a function of stock size, and can be represented as

$$f^*(X) = \frac{PqX - c_i}{2c_s} \tag{3.13}$$

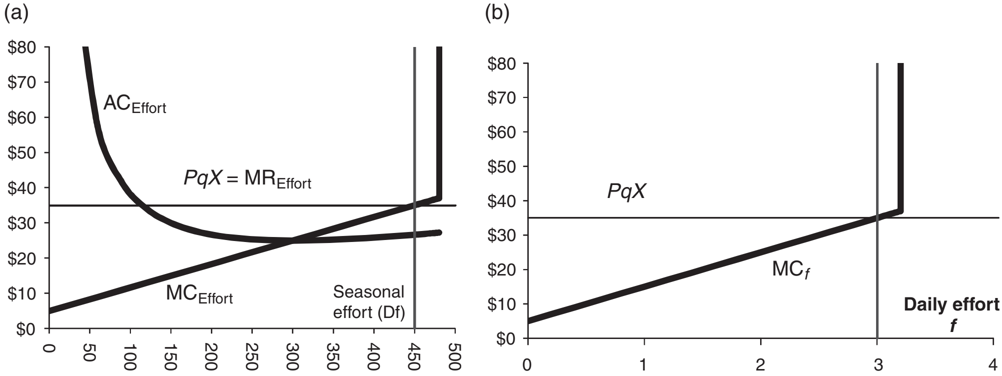

Figure 3.4 Seasonal and daily average and marginal cost of effort.

More formally, given the constraint on maximum effort, the decision rule for production will be:

$$f^*(X) = \min\left[\frac{(PqX - c_i)}{2c_s}, \max f\right] \quad \text{if } (PqX - c_i) > 0 \tag{3.14}$$

$$f^*(X) = 0 \quad \text{if } (PqX - c_i) < 0 \tag{3.15}$$

The interpretation of this is as follows. At high stock sizes, $\left\{X > \frac{[2c_s(\max f) + c_i]}{Pq}\right\}$, vessels will produce at their maximum output level, while at lower stock sizes, $\left\{X < \frac{c_i}{Pq}\right\}$, it will not be profitable to operate because revenues will be less than variable costs. Over the intermediate range, the profit-maximizing level of f will depend on stock size.

This can be demonstrated graphically using Figure 3.4b, which shows the relevant curves for daily production. The MC(f) curve is monotonically increasing over the range from zero to max f. At that point, the marginal cost curve can be represented as a vertical line. The marginal revenue of daily effort is PqX. The optimum output level occurs where PqX equals MC(f). Given the stock size which produces the PqX curve in the figure, the optimum daily level of effort will be 3. If stock size is such that the PqX line intersects the vertical axis below the vertical intercept of the MC(f), optimal output will be zero. At the other extreme, if the PqX line intersects anywhere in the vertical portion of the MC(f), the optimal output will be max f.

Given the fixed number of operating days, it is straightforward to translate the curves for daily analysis into cost curves for seasonal effort. Seasonal average cost is expressed in Equation 3.7. The seasonal output is simply the product of daily effort and $D_{\max}$. The relationship between seasonal marginal cost and daily marginal cost is as follows:

$$\mathrm{MC}(f) = \mathrm{MC}(D_{\max} f) \tag{3.16}$$

Technically there are an infinite number of ways to produce a given amount of seasonal output, depending on how many days the boat operates and how much effort is produced per day. But in this specification, there is only one way to produce a given seasonal output level and that is to operate at the required level of f for the fixed number of fishing days. This is the reason that Equation 3.16 holds. This is not as artificial as it may appear. This rule will guarantee that the total variable cost of producing the given level of production will be minimized. The production will be spread out over the allowable production period such that the marginal cost of the last unit produced will be the same on each day.

It is convenient to use the seasonal cost curves to analyze operating decisions because the level of profits can readily be determined from the graph. The optimal level of seasonal effort follows from the same decision rule as for optimal daily effort. The vessel will maximize profits by operating where PqX equals $\text{MC}(D_{\text{max}}f)$. Given the stock size that will generate the PqX line in Figure 3.4a, the vessel should produce 450 units of effort for the year. The vessel will be earning positive profits at this point because the return per unit of effort is greater than the average cost (AC) of effort. In this case, there would be a tendency for vessels to enter the fishery.

It is easily seen that if the PqX line intersects the $\text{MC}(D_{\text{max}}f)$ curve below the average cost curve, the vessel will not be making economic profits and vessels will tend to leave the fishery. The figure very clearly demonstrates the relationship between changes in stock size and changes in vessel profitability. It follows that the economic equilibrium will occur at that stock size where the PqX line intersects the $\text{MC}(D_{\text{max}}f)$ curve at the minimum of the AC curve. That is, the open access equilibrium will occur at that stock size where the PqX line is just tangent to the AC curve. An important sidelight of this is that at the open access equilibrium, vessels will be forced to operate such that the average cost of producing effort is minimized.

The bioeconomic equilibrium occurs where PqX equals both the average and the marginal cost of effort. As such, the vessels will be operating at f_{min} (see Equations 3.7 and 3.8). Using Equation 3.10, the equilibrium stock size can be expressed as follows:

$$X_{\text{BE}} = \frac{\left[c_i + c_s f_{\text{min}} + (\text{FC}/f_{\text{min}} D_{\text{max}})\right]}{Pq} \tag{3.17}$$

Given our assumptions, this is equivalent to Equation 3.2.

Before going on, it will be useful to anticipate the discussion of the economic effects of regulation, which will be presented later. One key point that follows from the above is that the bioeconomic equilibrium stock size is dependent on prices, costs, and the productivity of effort (see Equation 3.17). If costs go up, the stock size will increase. And as a matter of fact, this is the bottom-line explanation of how many traditional regulations increase stock size. Directly or indirectly, they increase the cost of producing effort. We will describe the microeconomics of this phenomenon below.

There are several ways to calculate the open access equilibrium fleet size, but perhaps the simplest is to use Equation 3.17 to calculate the open access equilibrium stock size. Because vessels will operate at $f_{\min}$ at this stock size, the open access equilibrium fleet size will be:

$$V_{\mathrm{BE}} = \frac{G(X_{\mathrm{BE}})}{[D_{\max} f_{\min} q X_{\mathrm{BE}}]} \tag{3.18}$$

This represents the number of vessels each operating at the minimum of their AC curves that it will take to harvest the sustainable yield from the open access stock size. In our example, this will be a fleet size of 14.12.

An important difference between the aggregate and disaggregate model is that in the former, the cost of effort is assumed constant. In the latter, the parameters of the cost function are constant, but the cost of effort will change with vessel operation. Therefore, the economic analysis of the maximum economic yield (MEY) is more complex because it is necessary to consider more than just how much effort should be used. It is also necessary to consider how it should be produced and how much it should cost.

We can take a more formal look at this by analyzing optimal utilization in terms of the disaggregated model in a way that is comparable to the discussion around Equations 2.16–2.19. The sustainable profit function that is analogous to Equation 2.16 is:

$$\Pi(V, f) = P[a(VfD_{\max}) - b(VfD_{\max})^2] - VC_v \tag{3.19}$$

This is the appropriate equation to consider optimal utilization because the effect of effort on long-run changes in stock size is subsumed in the sustainable yield function. In this case, there are two control variables: the number of vessels and the daily effort produced by each. To find the static MEY point, we want to find the combination that will maximize total profits. After some manipulation, the first-order conditions for profit maximum with respect to V and f can be expressed as follows:

$$\frac{\partial \Pi}{\partial V} = P\,[a - 2b(VfD_{\max})] - \frac{C_v}{(fD_{\max})} = 0 \tag{3.20}$$

$$\frac{\partial \Pi}{\partial f} = P\,[a - 2b(VfD_{\max})] - \frac{\partial C_v}{\partial f}\left(\frac{1}{D_{\max}}\right) = 0 \tag{3.21}$$

Before interpreting these conditions, note that they can only hold simultaneously if:

$$\frac{C_v}{(fD_{\max})} = \frac{\partial C_v}{\partial f}\left(\frac{1}{D_{\max}}\right) \tag{3.22}$$

Since the left-hand side is equivalent to Equation 3.7, the average cost of effort, and the right-hand side is equal to Equation 3.8, the marginal cost of effort, this means that f will have to equal $f_{\min}$ if the profit-maximizing level of aggregate effort is to be produced. While the mathematics may be a little complex, the principle is simple. Part of the solution to optimal utilization is that vessels must operate at their most efficient level. More formally, as a pair the first-order conditions can be interpreted as follows. The first term of both is the marginal *sustainable* return for a unit of effort (see Equation 2.18). There are two margins along which effort can be expanded. More vessels can be added to the fleet and, in addition, each existing vessel can produce more effort. The return from adding another boat should equal the marginal cost of producing an extra unit of effort by adding another vessel, and, in addition, the return from adding another unit of effort to a vessel should equal the marginal cost of producing that effort. In addition, the cost of producing that last unit of effort on both margins should be the same.

Given that f must equal $f_{\min}$, the solution for the optimum fleet size can be found using either Equation 3.20 or 3.21. Using Equation 3.20, we have:

$$V_{\text{MEY}} = \frac{\left[Pa - C_E^*\right]}{[2Pbf_{\min}D_{\max}]} \tag{3.23}$$

Given the parameters in Table 3.1, the optimal fleet size is 7.06. The optimal amount of aggregate effort is therefore equal to $V_{\text{MEY}}\, f_{\min} D_{\max}$, which will produce the same value as Equation 2.19. There will be more detail in the exercises for this chapter.

3.4.2 Dynamics in the disaggregated model

The building blocks of the dynamic analysis are the EEC, the PEC, and the trajectory curve. Consider how they will change when using the disaggregated model. One fundamental change is that the control variable is fleet size rather than aggregate effort, and so the horizontal axis is measured in terms of vessels. This will affect the PEC and the trajectory but not the EEC. The equilibrium stock size is independent of fleet size, as expressed in Equation 3.17.

Using a traditional interpretation, the PEC shows a combination of stock and effort where catch will equal growth. In terms of the disaggregated analysis, it can best be thought of as the number of boats that can be supported at any stock size taking into account how stock size will affect vessel behavior with respect to the production of f. This curve can be derived using the following equation:

$$G(X) = VD_{\max}qXf^*(X) \tag{3.24}$$

The left-hand side is stock growth and the right-hand side is the harvest that will be obtained by a given fleet for a given stock size. The term $f^*(X)$ is the profit-maximizing amount of daily effort; see Equation 3.14. Recall that $f^*(X)$ will equal max f at certain stock sizes. Solving for V obtains:

$$V = \frac{G(X)}{[D_{\max}qXf^*(X)]} \tag{3.25}$$

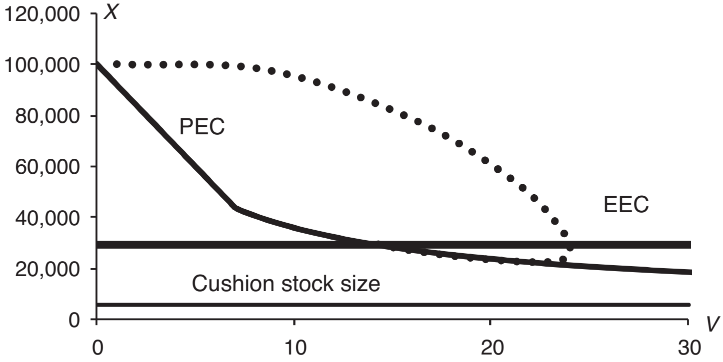

Figure 3.5 Open access time path for stock and fleet size using the disaggregated model.

The EEC and the PEC in terms of vessels are pictured in Figure 3.5. Note that the PEC is not a straight line as in the aggregate case because the amount of effort per vessel is inversely related to stock size. That is, as stock size decreases, the vessel daily amount of effort decreases as well, and so more boats can be accommodated than would be the case if effort were to remain constant. Note that at very low stock sizes, the number of boats that can be accommodated becomes quite large because the daily optimal amount of effort approaches zero.

The trajectory follows from the equations for the change in stock and fleet size which in this case can be represented as:

$$X_{t+1} = X_t + G(X_t) - qV_t f^*(X_t) D_{\max} X_t \tag{3.26}$$

$$V_{t+1} = V_t + \varphi_1 \pi_{v(t)} \tag{3.27}$$

In order to make the dynamic results of the aggregate and the disaggregate model similar, it will be necessary to calibrate the entry/exit coefficient because entry and exit take place in the form of vessels rather as individual units of effort. In the original formulation, the change is in terms of units of effort (see Equation 3.4).

$$\Delta E = \varphi(PqX_t - C_E) \tag{3.28}$$

From Equations 3.10 and using $f_{\min}$ in order to get a constant value, we have

$$\Delta V = \varphi_1(PqX - C_E^*) D_{\max} f_{\min} \tag{3.29}$$

where φ_1 is the new coefficient for which we are searching. Multiplying Equation 3.29 by $D_{\max}{}^* f_{\min}$ will give an expressioin for the total change in effort which results from the change in fleet size. Setting that equal to Equation 3.28 and solving for φ_1, we have

$$\varphi_1 = \frac{\varphi}{[D_{\max} f_{\min}]^2} \tag{3.30}$$

The value that falls out for our example is provided in Table 3.1.

The open access time path for stock and fleet size is also pictured in Figure 3.5. Given the way the cost conditions have been specified, the system will reach an equilibrium at the same stock size and total effort combination as in the aggregate model, but the time path is quite different. The trajectory is a more direct path to the equilibrium. Compare Figure 3.2a. It will be demonstrated in the exercises given in the CD that when effort per vessel remains constant, the more cyclical trajectory occurs even when effort is defined in terms of vessels.

The reason for the difference in the trajectories is that there are two factors that help to bring the system to an equilibrium. In the disaggregated model, changes in stock bring about changes in both fleet size and daily effort, and the cumulative effects work together to hasten the path to equilibrium. Look at this in another way. Because vessel operators decrease daily effort with decreases in stock size, there is much less volatility in the system. As the stock size decreases, it is not exploited as heavily for any given fleet size as it would if daily effort remained constant. Note that the PEC in the aggregate model is much further to the right. This means that the stock can accommodate a larger fleet and still have catch less than growth.

This phenomenon is demonstrated graphically in Figure 3.6, which shows the time path of fleet size and total effort as the fishery moves along the trajectory in Figure 3.5. Note that because of the decrease in effort per day, total effort actually starts to fall while the number of vessels is still increasing. Further, total effort approaches the equilibrium level much sooner than the fleet size does. This means that in the latter part of the trajectory, fleet size may be changing but there is little effect on the total amount of effort.

There is an interesting aspect of the disaggregated model that is related to the fact that vessels will not operate if the stock is less than c_i/pq (see

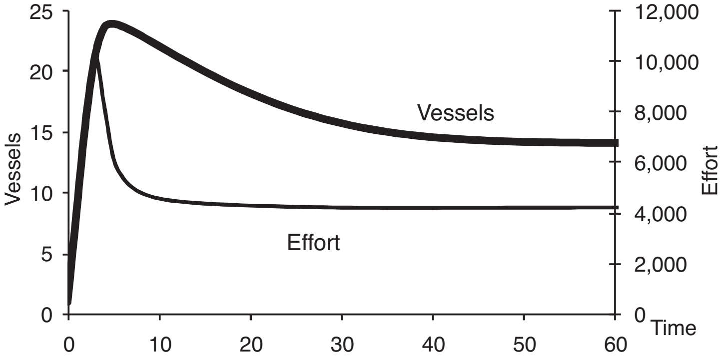

Figure 3.6 Comparative time paths for fleet size and total effort.

Equation 3.15). We can call this the cushion stock size because once the trajectory curve hits this point, it will bounce back up because stock will grow when effort falls to zero. This cushion stock phenomenon puts a different perspective on the possibility of a stock being pushed to extinction by open access fishing than is possible using the aggregate model.

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Chapter 4

Optimal dynamic utilization

4.1 Introduction

It is now time to return for a more complete discussion of the economically efficient utilization of a fishery. The static analysis presented in previous chapters is sufficient to explain the basic concept and to demonstrate why an open access system with no or incomplete property rights will provide incentives that will often lead to an inefficient combination of effort and stock size. However, static analysis precludes the consideration of the time it takes the fish stock to adjust to changes in effort. And this is critical to understanding the complex nature of the gains and losses of different temporal harvest patterns. Over time, the size of a fish stock will change on its own and as a result of fishing mortality. These changes affect the actual and potential net revenues that can be earned.

Heavy fishing in the current period will generate gains but at the expense of a smaller fish stock and smaller potential gains in the future. Alternatively, reducing or maintaining low fishing pressure now will allow more fish to grow and reproduce, allowing for higher potential gains in the future, but there will lower benefits from fisheries utilization in the present. This is the fundamental issue of fisheries conservation. It is necessary to consider the trade-off between catching another fish now and letting it remain in the sea. This is a much more complicated problem than it may first appear. It requires the simultaneous consideration of population dynamics, harvest technology, valuation of fish products, time preferences, as well as the rate of return on other sources of investment. From an economic point of view, in order to obtain the dynamic optimal utilization of a fish stock, it is necessary to select a long-term harvest strategy that will maximize the present net value of output. Starting with a status quo stock size, optimal utilization can be defined in terms of a time path of effort. The time path of effort will generate time paths of both harvest and stock size. The time path of effort that we are looking for is the one that will generate highest net present value (NPV) of harvest.

For pedagogical purposes, it is useful to consider the problem by focusing on stock size. Further, the problem can be divided into two separate parts. First, where do we want to go? That is, what stock size do we ultimately want to obtain if the goal is to maximize the NPV of profits? Second, how do we get there? That is, how should effort be applied over time such that the combination of catch and growth will cause the stock to move to the desired level in such a way that the NPV of harvest is maximized?

Before moving on, it is necessary to repeat that the real goal of optimal utilization is the appropriate use of the living resource and of the inputs that are used to harvest them. It is not the maximization of profits per se that is important. Optimal use must consider the opportunity cost of using inputs to produce effort. It is not the gross amount or even the value of fish products that is important. From an economic point of view, it does not make sense to produce more fish if the production of the required effort causes the value of goods and services produced elsewhere in the economy to fall by an amount larger than the value of the fish produced. Focusing on profits will take these opportunity costs into account.

Clark and Munro (1975) are normally credited with the first comprehensive treatment of dynamic optimal utilization. Prior to this, the great majority of work used static analysis, which failed to treat the fish stock as a capital good. (See Anderson, 2002, for a brief history of the development of the economic theory of fisheries utilization.) Clark and Munro use a linear short-run production function identical to the one in Chapter 2. They derive a "Golden Rule" equation, which provides an explicit answer to the "where to go" question. In terms of the linear model, the answer to the "how to get there" question, while correct, is not very interesting. The solution is a "bang-bang" approach where no fishing is allowed if the current stock is below the optimal one and where the maximum possible amount of effort is used if the current stock is above the optimal. No matter where you are, get to the optimal stock size as quick as possible.

The analysis here will be analogous to the pioneering work of Clark and Munro, but we will use a nonlinear production function and the analysis will be in terms of effort. This allows for a more nuanced answer to the "how to get there" question. It also provides a more complete comparison between the stationary optimal utilization point and the open access bioeconomic equilibrium.

The chapter will proceed as follows. First, the deterministic aggregate model of Chapter 2 will be expanded by introducing a short-run yield curve that is nonlinear in both effort and stock size. The second section will provide a formal mathematical derivation of the optimal solution. More important for this discussion, however, will be the economic interpretation of the various conditions. The discussion will look at both the "where do we go" and "how do we get there" questions. It is difficult to obtain an exact solution to the second question, but the principles can be explained relatively easily. A technique for obtaining the actual solution will be covered in the exercises for this chapter given in the CD.

4.2 The general model with nonlinear yield functions

Following the standard analysis in much of the current literature, and for ease of exposition, a linear short-run yield function has been used in the above models. However, because of the nonlinearity of the growth function, the sustainable yield curve is nonlinear, which makes it possible to solve for the static optimal utilization point. The dynamic analysis uses short-run functions, and so it is necessary to introduce nonlinearities in order to provide an analogous discussion. This can be accomplished by using the following general short-run yield function.

$$y = qX^{\beta_1}E^{\beta_2} \tag{4.1}$$

The linear yield function used above (see Equation 2.6) is a special case of Equation 4.1, where the exponents are both equal to 1.

As in previous chapters, numerical examples will be used to facilitate the discussion. Two separate cases will be used for reasons that will become clear below. In Case 1, it will be assumed that $\beta_1 = 1$ and $\beta_2 < 1$. This means that there are constant returns to stock size but diminishing marginal returns to effort. In Case 2, it is assumed that $\beta_1 = 0$ and $\beta_2 < 1$. This represents the special case where yield is not a direct function of stock size. This phenomenon can occur in a schooling fish such as herring. Theoretically, it can cause serious problems if fishing continues on the smaller schools until it results in the destruction of the stock. By comparing these two cases, it will be possible to provide a detailed explanation of the "stock effect" in fisheries utilization. The values used in the specific examples are listed in Table 4.1. The exponents in the yield function necessitate changes in the catchability and the exit/entry coefficients in order to keep the models internally consistent and comparable to the cases discussed above. The full implications of these changes will be discussed in more detail below.

4.2.1 The PEC and EEC for Case 1

Relative to the linear models, there are some differences in the economic equilibrium curve (EEC) and the population equilibrium curve (PEC) in nonlinear models that are worth exploring. But in addition, the graphical analysis provides a good framework for analyzing the optimal dynamic utilization problem. The PEC is generated by equating the growth curve and the short-run yield curve and solving for X. Using the Case 1 assumptions, this is:

$$rX\left(1 - \frac{X}{K}\right) = qXE^{\beta_2} \tag{4.2}$$

$$X = K - \left(\frac{Kq}{r}\right)E^{\beta_2} \tag{4.2a}$$

Table 4.1 Economic parameters and equilibrium values for Case 1.

	Symbol	**Value**		
Biological parameters				
Intrinsic growth rate	r	0.3		
Carrying capacity	K	100,000		
Initial stock size	X_{initial}	95,000		
Economic parameters		Case 1	Case 2	
Price of fish	P	\$17.00	\$17.00	
Cost per unit of effort	C_E	\$25.00	\$25.00	
Standard catchability coefficient	q	0.000050	0.000050	
New catchability coefficient	q'	0.000263	8	
Discount rate	δ	12.0%	12.0%	
Stock coefficient	β_1	1	0	
Effort coefficient	β_2	0.8	0.8	
Entry/exit coefficient	φ	25	50	
Initial effort	E_{initial}	400	300	
Equilibrium values				
Maximum sustainable yield	Y_{MSY}	7,500	7,500	
Bioeconomic equilibrium yield	Y_{BE}	6,275	7,006	
Static maximum economic yield	Y_{MEY}	6,772	2,870	
Stock at MSY	X_{MSY}	50,000	50,000	
Stock at BE	X_{BE}	29,795	62,829	37,171
Stock at static MEY	X_{MEY}	65,582	89,286	10,714
Effort at MSY	E_{MSY}	2,792	5,188	
Effort at BE	E_{BE}	4,267	4,764	
Effort at static MEY	E_{MEY}	1,750	1,561	

For completeness, it is also possible to derive the sustainable yield curve for this case. Substituting Equation 4.2a into Equation 4.1, noting that β_1 is assumed to equal 1, we have:

$$Y = aE^{\beta_2} - bE^{2\beta_2} \tag{4.3}$$

where again $a = qK$ and $b = Kq^2/r$. Compare Equation 2.8. The presentation of the new sustainable revenue and cost curves will be left to the exercises for this chapter. However, the stock sizes at the bioeconomic equilibrium and the static maximum economic yield (MEY) will be useful to our analysis, and they are noted in Figure 4.1.

The total revenue curve in terms of stock size will also be important to the analysis and is presented in Figure 4.3 below. In this case, the level of effort that is necessary to take a catch equal to growth at any stock size is $\{[(K - X)r]/qK\}^{1/\beta_2}$ (see Equation 2.14).

The new EEC is generated by setting total revenue equal to total cost and solving for X as follows:

$$PqXE^{\beta_2} = EC_E \tag{4.4}$$

$$X = \frac{C_E}{PqE^{\beta_2 - 1}} \tag{4.4a}$$

Both the new PEC and EEC are nonlinear and are pictured in Figure 4.1. The diminishing marginal returns to E cause the PEC to be convex to the origin. For the same reason, the EEC is no longer horizontal, but an upward sloping curve. As stock size increases, it takes larger amounts of effort to cause profits to fall to zero. As before, the bioeconomic equilibrium will occur at the intersection of these two curves. The trajectory analysis will be left as an exercise given in the CD.

The EEC shows the combinations of E and X, where total profits are equal to zero. For the purposes of discussion, it will also be useful to have another economic frame of reference. Consider the short-run profit function.

$$\Pi = PqXE^{\beta_2} - EC_E \tag{4.5}$$

Taking the first derivative with respect to E, setting it equal to zero and solving for X generates an equation which shows the combinations of E and X, where current annual profits are maximized for the given level of X.

$$\beta_2 PqXE^{\beta_2 - 1} - C_E = 0 \tag{4.5a}$$

$$X = \frac{C_E}{\beta_2 PqE^{\beta_2 - 1}} \tag{4.5b}$$

Call this the annual MEY curve. It is also depicted in Figure 4.1. Note that at every point above the curve, effort is less than is necessary to maximize current profits for the specified level of X. Call the stock size at which the annual MEY curve and the PEC intersect X_∞ for reasons that will become clear below.

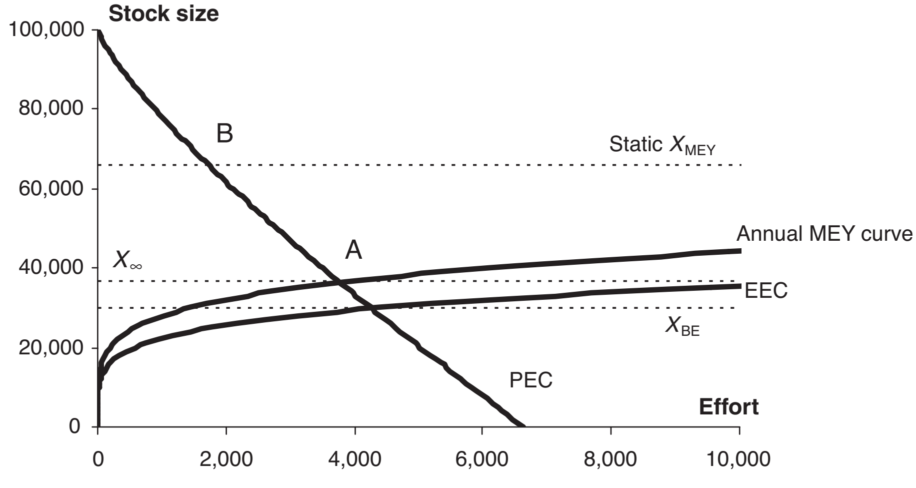

Figure 4.1 Annual maximum economic yield (MEY) and corresponding EEC and PEC for Case 1.

The annual MEY curve can be expressed in a different way that will be useful when interpreting the conditions for dynamic optimal utilization. Using implicit yield functions, current profit can be expressed as:

$$\Pi = Py(E, X) - C(E) \tag{4.6}$$

The first-order condition for maximum profit is that the marginal revenue of effort equals marginal cost of effort. (For ease of interpretation, the following notation will be used for derivatives: $dG(X)/dX = G'$, $dC(E)/dE = C'$, $dy/dX = y_x$, and $dy/dE = y_E$.)

$$Py_E - C' = 0 \tag{4.6a}$$

Dividing through by y_E obtains:

$$P - \frac{C'}{y_E} = 0 \tag{4.6b}$$

The term C'/y_E will be recognized as the marginal cost of fish. This term provides the profit maximizing condition in terms of output rather than effort. The maximization of current profits requires that the price of fish equals the marginal cost of fish.

Even at this stage, this analysis can provide some hints to the answer of the "where to go" question. If the optimal stock size is to be sustainable, then it must lie somewhere on the PEC, because this is the collection of points where catch equals growth. Further, the stock size must be larger than X_{BE}, the bioeconomic equilibrium stock size, because at that point on the PEC, profits are zero. So for a start, we can say that the optimal stock size must be somewhere on the PEC somewhere above X_{BE}. It is possible to go a little further, however. At any point to the right of the annual MEY curve, current profits will be less than the maximum possible. Therefore, a decrease in effort would make sense from both a static and a dynamic point of view. Current profits would go up and stock size would increase providing for higher future profits. Therefore, we can conclude that the optimal stock size will have to be somewhere at or above point A on the PEC. At the other end, we know that sustainable net returns are maximized when the stock is equal to static X_{MEY}. Therefore, it would not make sense for the optimal stock size to be higher than this level. Even at this level of abstraction, we can say that the optimal stock size must be somewhere between points A and B on the PEC.

4.2.2 The PEC and EEC for Case 2

Consider now the case where β_1 equals zero. Because X^0 equals 1, the yield curve can be represented as follows:

$$y = qE^{\beta_2} \tag{4.7}$$

Therefore, the PEC can be expressed as follows:

$$rX\left(1 - \frac{X}{K}\right) = qE^{\beta_2} \tag{4.8}$$

Solving for E obtains:

$$E = \left\{\left(\frac{r}{q}\right) X\left(1 - \frac{X}{K}\right)\right\}^{1/\beta_2} \tag{4.8a}$$

Because the growth curve has an inverted U shape, the PEC will have an analogous shape with respect to X. For every level of E, there will be two levels of X where catch will equal growth (see the PEC in Figure 4.2).

The Case 2 profit function is:

$$\Pi = PqE^{\beta_2} - EC_E \tag{4.9}$$

The EEC can be obtained by solving Equation 4.9 for E, and the annual MEY curve results from setting the first derivative of the profit function with respect to E equal to zero and then solving for E. These two equations are as follows:

$$\text{EEC}: E_{\text{BE}} = \left\{\frac{C_E}{Pq}\right\}^{1/(\beta_2 - 1)} \tag{4.9a}$$

$$\text{Annual MEY}: E_{\text{MEY}} = \left\{\frac{C_E}{\beta_2 Pq}\right\}^{1/(\beta_2 - 1)} \tag{4.9b}$$

Both E_{BE} and E_{MEY} are constants and not functions of stock size. These two curves are also pictured in Figure 4.2, given the Case 2 parameter values. Because catch is not a function of stock size, these curves have different implications. In Figure 4.1, higher stock sizes can support a higher equilibrium level of effort, and it takes a higher level of effort to maximize net returns for any stock size. In this case, as pictured in Figure 4.2, stock does not matter in this regard. This can lead to problems with stock depletion, as discussed below.

While there are significant differences between the graphs in Figures 4.1 and 4.2, the interpretation is the same. The bioeconomic equilibrium will occur at the intersection of the PEC and the EEC. There are two possible equilibrium points, one at $X_{\text{BE}(h)}$ and the other at $X_{\text{BE}(l)}$. The relative position of the EEC and the annual MEY curve with respect to the PEC is dependent on the price–cost ratio. Higher price–cost ratios will cause the set of curves to shift to the right. If the EEC is so far to the right that it does not intersect the PEC, there will be no bioeconomic equilibrium. Regardless of stock size, the short-run profit-maximizing level of effort will cause catch to be greater than growth. The implications will be discussed below and in the exercises given in the CD.

The trajectory analysis is somewhat different in this case. As discussed in Chapter 3, the open access path to equilibrium depends on the relative changes

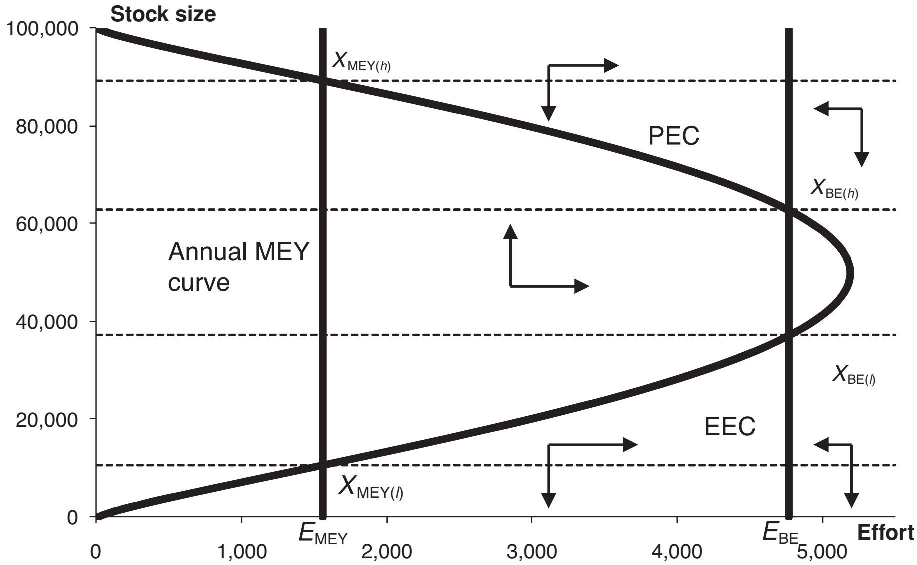

Figure 4.2 Annual maximum economic yield (MEY) and corresponding EEC and PEC for Case 2.

in X and in E at various points in the graph. At all points to the right of the EEC, effort will tend to decrease because profits are less than zero, and vice versa. Changes in stock size are a little more difficult to explain but at all points to the left of the PEC, stock size will increase. To the right of the curve, stock size will decrease. Remember that this is the case where catch does not vary with stock size. Pick any point on the upper part of the PEC curve which is associated with the right-half of the growth curve, where increases in stock size cause growth to decrease. Catch will equal growth. At any level of effort, as stock size increases, growth will decrease and catch will be less than growth. Therefore, at any point above the PEC, stock size will be falling. By reversing the logic, it follows that at any point immediately below the top-half of the PEC, stock size will be increasing.

The lower-half of the PEC represents the left-hand side of the growth curve where an increase in stock size increases growth. Therefore, at any level of effort, as stock increases, growth will increase but catch will remain the same, and so stock size will increase. Therefore, at any point inside the PEC, the stock size will be increasing.

Now for any level of effort, consider a movement from a point on the lower-half of the PEC to a point below it. At lower stock sizes, growth will decrease but catch will remain the same, and so the stock will be decreasing. Finally, at any point to the right of the maximum effort on the PEC, there is no corresponding stock size where catch will equal growth, and so for these levels of effort, stock size will always fall. These relationships are summarized by the arrows in Figure 4.2.

While there are two possible equilibrium points, only the one at $X_{BE(h)}$ is stable. To see this note that, depending on the size of the entry/exit coefficient, at any point to the left of the EEC and above the bottom-half of the PEC, the operation point will be moving toward an equilibrium at point A. Points to the right of the EEC at higher stock sizes are problematic. Both stock and effort will fall, and so the operation point could move toward the equilibrium, but it could also move to a point below the PEC. In this range, it can be seen that stock size will continue to fall which will start a trajectory for the extinction of the stock. This will be demonstrated in more detail in the exercises given in the CD.

The annual MEY curve can provide preliminary information on optimal utilization in this case as well. From a current period's point of view, it will never make sense to operate to the right of this curve because increases in effort in this range will decrease current profits.

4.3 Formal analysis of optimal dynamic utilization

The problem of dynamically efficient utilization of a fishery can be thought of as an optimal control problem. The fish stock is an asset that is capable of producing a flow of benefits through time. It is the state variable which, taking natural population dynamics into account, can be adjusted by changing effort. Effort is the control variable. The problem is to adjust the state variable over time through changes in the control variable so as to maximize the NPV of output.

The analytics of the problem are quite complicated and will not be discussed in detail here. It is based on the Pontryagin principle and it involves setting up a function called the Hamiltonian and then using it to derive certain conditions. The analysis has been a fundamental part of modern fisheries economics since the pioneering work of Clark and Munro. Readers who desire more detail on the formal mathematics are referred to the works cited in the references to this chapter.

In order to make the analysis completely general, implicit functions for short-run yield, cost, and growth will be used. Specific explicit functions will be used when discussing the two cases below.

Profit in any year is:

$$\Pi(t) = Py(E(t), X(t)) - C(E(t)) \tag{4.10}$$

where $y()$ is the short-run yield curve and C() is the cost function. It is assumed that both are continuous and twice differentiable. The present value (PV) of profits over time is:

$$PV = \int_0^\infty e^{-\delta t}\Pi(t)\,dt \tag{4.11}$$

where δ is the social discount rate. The problem is to find the time path of effort that will maximize Equation 4.11 subject to the following:

$$0 \leq E(t) \leq E_{\max}$$

$$X(t) > 0$$

$$\frac{dX}{dt} = G(X(t)) - y(X(t), E(t))$$

$E_{\max}$ is the maximum amount of effort that can be produced in any year. Its relevance will be made clear below. The other conditions state that stock size must be positive at all times and that the net change in stock size is determined by the difference between growth and harvest.

The Hamiltonian for the problem is:

$$H = e^{-\delta t}\,[Py(E(t), X(t)) - C(E(t))] + \lambda(t)\,[G(X(t)) - y(X(t)), E(t))] \tag{4.12}$$

The first term is the PV of annual profits and the second term is a constraint that tracks the change in stock size. The term $\lambda(t)$ is called the *costate variable*. It is the shadow value of the marginal unit of stock in time t discounted back to the present. The shadow value represents the marginal value of stock in terms of the increase in the NPV of harvest that would result from increasing stock size by one unit in the given period. In other words, while the price, P, represents the value of a unit of fish on the dock, $\lambda(t)$ represents the value of a unit of fish in the ocean at time t discounted back to the present. This will become more clear in terms of the illustration provided below.

The requirements for maximum to the Hamiltonian are:

$$\frac{\partial H}{\partial E} = 0 \text{ at each point in time} \tag{4.13}$$

$$\frac{d\lambda}{dt} = \frac{-\partial H}{\partial X} \tag{4.14}$$

4.3.1 Where to go: technical derivation of the Golden Rule

While both conditions are necessary for a complete solution to the problem, Equation 4.13 is useful for answering the "how to get there" question and Equation 4.14 provides a start to look at the "where do we go" question. However, the solution to Equation 4.13 also provides a critical link for answering the second question.

Evaluating Equation 4.13 obtains:

$$\left[Py_E - C'\right] = e^{\delta t}\lambda(t)y_E \tag{4.13a}$$

This can also be represented as follows:

$$\left[P - \frac{C'}{y_E}\right] = \lambda(t)\,e^{\delta t} \tag{4.13b}$$

The term in parenthesis on the left-hand side is a repeat of the price minus marginal cost of fish condition introduced in Equation 4.6b.

The evaluation of Equation 4.14 yields:

$$\frac{d\lambda}{dt} = -e^{-\delta t}\left[P y_x\right] + \lambda(t)\left[y_x - G'\right] \tag{4.14a}$$

Taking the time derivative of Equation 4.13b obtains:

$$\frac{d\lambda}{dt} = -\delta e^{-\delta t}\left[P - \frac{C'}{y_E}\right] \tag{4.15}$$

Evaluating Equations 4.14a and 4.15, taking into account the value of $\lambda(t)$ in 4.13b, and solving for δ obtains:

$$G' + \frac{y_x\left[C'/y_E\right]}{\left[P - (C'/y_E)\right]} = \delta \tag{4.16}$$

Equation 4.16 is the equivalent of the Golden Rule equation derived by Clark and Munro, given that our analysis is in terms of effort. This is a single equation with two unknowns, X and E. However, since we are looking for the optimal steady-state stock size, we know that growth must equal catch.

4.3.2 Where to go: heuristic derivation of the Golden Rule

Before interpreting the Golden Rule, let us first provide a more casual derivation of the same equation using a process that will allow for a more intuitive interpretation of the results (see Bjørndal and Munro, 1998). The question at hand is the determination of the dynamically optimal stock size. Think of it as an investment problem. What is the return on investment? What is gained by adding a unit of fish stock? What does it cost to add another unit of stock? What is lost by making the investment? If an investment that will provide an annual return of $10 per year in perpetuity can be purchased for $100, it will have an internal rate of return (IRR) of 10%. This return is calculated by dividing the annual return ($10) by the purchase price ($100). Is this a good investment? The answer depends on the market rate of interest. Assume that the interest rate is 7.5%. Putting $100 in the bank would yield an annual return of $7.50, which is lower that the return from the hypothetical investment. Since the investment has an IRR that is higher than interest rate, it is a good investment. More formally, if the quotient of the annual return and the price of investment is greater than the interest rate, making the investment will be profitable.

The same kind of logic can be applied to making investments in stock size. One difference is that the annual return in perpetuity and the cost of investing will change with stock size. But the same principle applies. As long as the IRR from adding another unit of stock is greater than the discount rate, it makes sense to increase stock size.

To look at this in more detail, consider Figure 4.3, which contains the sustainable revenue and cost curves in terms of stock size, given Case 1 parameters.

(Using the Case 2 parameters will lead to different shaped graphs, and the implications will be explained below.) The same curve in terms of the linear model is presented in Figure 2.7b. The bioeconomic equilibrium stock size and the static MEY stock size are indicated. It is obvious that the optimal stock size will have to be larger than X_{BE} because only over that range is the sustainable profit greater than zero.

As a sidelight, note that the static MEY stock is greater than X_{MSY}. While this does not always occur for a dynamic MEY (see below), recent work by Grafton, Kompas, and Hilborn (2007) suggests that it will often be the case.

Review for a moment the equations behind the graph. First, it is necessary to express everything as a function of stock size only. Continuing to use the implicit functions, a sustainable yield will occur at those combinations of E and X where growth is equal to catch.

$$y(X, E) - G(X) = 0 \tag{4.17}$$

In order to express profit as a function of stock size only, it is necessary to solve Equation 4.17 in terms of X.

$$E = E(X) \tag{4.17a}$$

This will be recognized as the inverse of the equation for the population equilibrium curve, PEC, which has been a prominent part of the discussion above. It should be noted that while, in some cases, the PEC can be double-valued (i.e., there are two values of E associated with some levels of X), the inverse will always be single-valued as long as the marginal productivity of E is positive. There will only be one level of E that can produce a harvest equal to growth for any stock size. This inverse curve shows the level of effort that is necessary to take the growth for any stock size. Substituting this into the short-run yield curve generates a sustainable yield curve as a function of X. The sustainable profit function is:

$$\pi = Py(E(X), X) - C(E(X)) \tag{4.18}$$

But we are interested in the change in sustainable profits that will result from an increase in stock size. This can be expressed as:

$$\frac{\partial \pi}{\partial X} = P\left[Y_E \frac{dE}{dX} + y_x\right] - C' \frac{dE}{dX} \tag{4.18a}$$

Using the rule for the differentiation of an implicit function, it can be shown from Equation 4.17 that:

$$\frac{dE}{dX} = \frac{G_X - y_x}{y_E} \tag{4.18b}$$

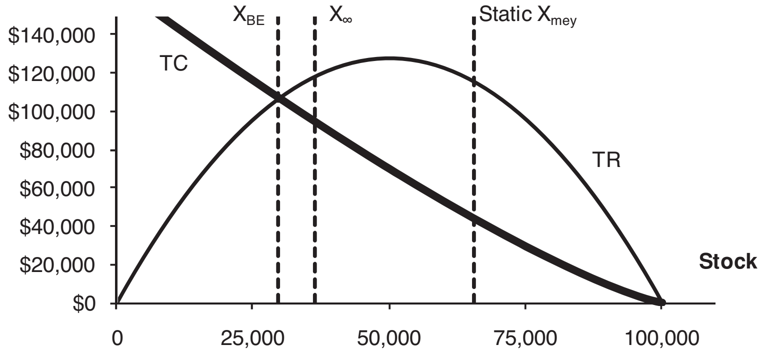

Figure 4.3 Sustainable revenue and cost curves in terms of stock size: Case 1.

Substituting this into Equation 4.18a and simplifying obtain:

$$\frac{\partial \pi}{\partial X} = \left[P - \frac{C'}{y_E}\right] G' + y_x \left[\frac{C'}{y_E}\right] \tag{4.19}$$

Equation 4.19 represents an expression of the sustainable annual gain from investing in one more unit of fish stock. This is the numerator of the expression for the IRR to the stock. The denominator is the cost of making the investment. But what is that cost? It is the foregone net income from not harvesting the unit of fish, which is $\left[P - (C'/y_E)\right]$. Therefore, the condition we are looking for to determine the optimal stock size is:

$$\frac{[\partial \pi/\partial X]}{\left[P - (C'/y_E)\right]} = \delta \tag{4.20}$$

Using Equation 4.19, it is obvious by inspection that Equation 4.20 is identical to Equation 4.16. The heuristic method of deriving the equation for optimal stock size produces exactly the same equation as does the technical Hamiltonian procedure.

4.4 Interpretation of the Golden Rule

For interpretation purposes, it will be useful to consider the Golden Rule equation in both forms: Equations 4.16 and 4.20. Both equations represent the IRR to the fish stock.

Let us interpret Equation 4.16 first. Given the two terms, it is possible to distinguish between the two types of return. Increases in stock size will affect both the amount of sustainable harvest and the amount of effort that is necessary to take that harvest. The term G' is the change in sustainable yield that results from increasing stock size. The slope of the growth curve can be interpreted as the own rate of return to the stock in physical terms. It is the change in growth divided by the change in stock size. The change in growth is the return and the change in stock size is the investment in stock that is necessary to bring about that return.

But there is more to the story because the change in stock also makes it easier to harvest the fish. The second term is $y_x[C'/y_E]/[P - C'/y_E]$. This is sometimes called the *marginal stock effect*. The term y_x is the marginal productivity of the stock. Keeping effort the same, a unit increase in stock will increase harvest by this amount. Further, C'/y_E is the marginal cost of taking a unit of catch. Therefore, the numerator is the cost savings that results from the stock effect. Some of the extra catch does not require an increase in effort. The denominator of the marginal stock effect is the opportunity cost of investing in a unit of stock. The cost savings provided by the marginal stock effect divided by the opportunity cost of investing in the stock is the second part of the IRR.

Using Equation 4.20, the other formulation of the Golden Rule, it is possible to identify the relevant range of potential optimal stock sizes. The graph of this function for the Case 1 values is pictured in Figure 4.4. Call this the IRR curve. The range over which the function is positive is narrowly proscribed. Note that the curve intersects the horizontal axis at the static MEY stock size. This is easy to explain. The numerator of the fraction is $\partial\pi/\partial X$ and this is positive but decreases as X approaches X_{MEY} from below, and it equals zero at X_{MEY}. At higher stock sizes, marginal return is negative. The IRR curve will always intersect the horizontal axis at X_{MEY}, the static MEY stock size.

The denominator of the expression is $\{P - (C'/y_E)\}$. Recall that at all points on the annual MEY curve, this expression is equal to zero. And we have defined the stock size where the annual MEY curve intersects the PEC curve as X_∞. As stock size is increased from X_∞, the value of $\{P - (C'/y_E)\}$ will increase because y_E increases. Therefore, as stock size approaches X_∞ from above, the value of the left-hand side of Equation 4.20 approaches infinity. Further, at stock sizes below X_∞, the denominator is negative, and so the IRR will be negative in this range as well. Therefore, it can be seen that the relevant range of the IRR function is between X_∞ and X_{MEY}.

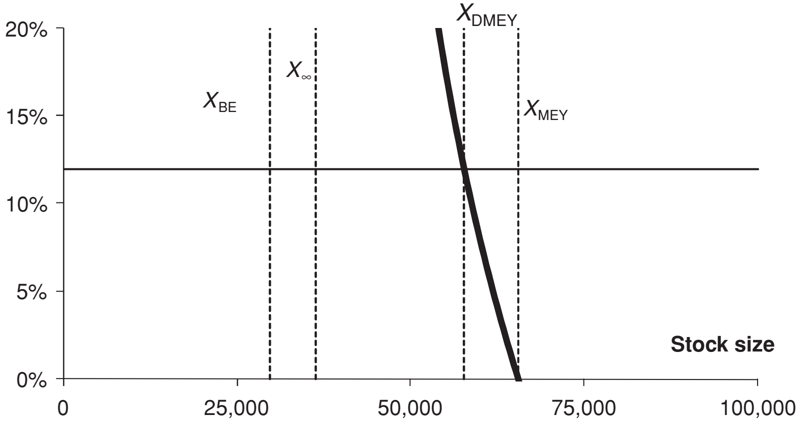

Figure 4.4 The internal rate of return (IRR) curve.

The optimal stock size occurs at the stock where the IRR curve intersects the horizontal line that represents the discount rate. This stock size can be obtained by solving Equation 4.20 for X. There is no clean analytical solution but it can be solved by numerical means. A procedure for doing so is demonstrated in the exercises for this chapter.

Going back to the discussion of Figure 4.1, it can now be seen that optimal stock size will be somewhere between points A and B on the PEC curve depending on the size of the discount rate. Consider how the size of the discount rate will affect the optimal stock size by looking at the two extreme values.

If the discount rate is infinite, there is no consideration given to profits earned in the future. In each year, the only concern will be to maximize current annual profits, given the existing stock size. This means that along the optimal utilization path, the correct effort level for any stock size will be described by the annual MEY curve. As a result, the fishery will eventually operate at X_∞. Consider the sustainable annual profits at this stock size (see Figure 4.3). They are positive but certainly smaller than could be earned at X_{MEY}. However, in order to obtain higher annual returns, it would be necessary to reduce current harvest so that stock size could be increased. But with an infinite discount rate, the increase in future returns will never compensate for the foregone current returns.

On the other hand, if the discount rate is equal to zero, net revenue has the same value no matter in which period they are earned. At this discount rate, it will make sense to go to the stock that generates the highest sustainable net revenue. At a zero discount rate, the dynamic MEY is equivalent to the static MEY. In summary, at an infinite discount rate, it is optimal to maximize current profits regardless of the stock size. This will lead to a stationary optimal stock size equal to X_∞. At a zero discount rate, the optimal stock size is X_{MEY}.

Given that the likely maximum discount rate is much less than infinity, the actual range of potential long-term stock sizes is considerably smaller than the range between X_∞ and X_{MEY}. In fact, depending on the parameters of the system, there will likely be a relatively small difference between the static MEY and the dynamic MEY stock sizes. Given this small difference, some might wonder if the emphasis on dynamic utilization is really worth the effort. But this misses the real contribution of dynamic analysis, which is the optimal time path of stock size. Regardless of how small the difference between the optimal stock size and X_{MEY}, the important question is how the stock size should be changed from the current one to the dynamically optimal one.

This version of the Golden Rule equation is better for interpreting the Case 2 situation, and the analysis is much simpler. However, there are some secondary issues that must be considered. Because y_x is zero in this case, Equation 4.16 is reduced to

$$G'(X) = \delta \tag{4.21}$$

The stock size should be such that the slope of the growth curve is equal to the discount rate. Call this stock size X_{DMEY}. There are no price and cost parameters in the equation but there is still an interesting economic interpretation. On the surface, this means that in this case, the optimal stock size will always be less than X_{MSY} because it is only in that range that G' is positive. Over this range, the annual sustainable harvest increases with increases in stock size. Increases in stock are good because they allow for a higher annual catch. But at some point, what is gained in terms of sustainable harvest is not worth what is given up in current harvest. In some instances, the solution of Equation 4.16 will not provide a correct solution for the optimal stock size because it ignores the cost of either pushing the stock down to, or letting it grow to, X_{DMEY}. The subtleties of this will be explained below.

4.4.1 How to get there?

Now that the economic logic of the determination of the dynamically optimal stock size has been established, we can move to the problem of determining the appropriate time path of harvest or effort to change the stock from whatever size it happens to be to the optimal stock size. To begin the discussion, consider Equation 4.13b. As discussed above, this condition must hold at all points along an optimal harvest path. As such, it can provide hints about how the level of effort should change through time. For convenience, it is rewritten in a slightly different form below.

$$\left[P - (C'/y_E)\right] = e^{\delta t}\lambda(t) \tag{4.22}$$

The left-hand side is the price of fish minus the marginal cost of fish. It is the net value of a unit of fish on the dock. Recall that $\lambda(t)$ can be interpreted as the shadow value of a unit of stock discounted back to the present. Therefore, the right-hand side can be interpreted as the current value of a unit of stock in place. But what does that really mean? The shadow value of a unit of fish biomass represents the increase in net value made possible by adding that unit of fish to the standing stock. So in output terms, optimal utilization will occur when the net value of the marginal unit of fish that is pulled out of the water each year is equal to the current value of a unit of fish left in the water.

Perhaps a better way to think about this is to put it in terms of an explicit time pattern of harvest. Since the expression must hold at all times during the transition to the optimal stock size, it means that the present net value of the last unit of fish caught in any period must have the same PV as the last unit caught in any other period. If this condition holds, the total PV of the net returns from the fishery must be maximized. This is so because there is no way to increase it by switching harvest from one period to another or by reducing harvest in any period to allow the stock to grow.

When looking at the problem from this point of view, it is clear why $\lambda(t)$ is interpreted as the shadow value of a unit of stock. Along the optimal time path, $\lambda(t)$ will equal the current net value of an extra unit of harvest in any period.

It is also useful to consider the optimal time path in terms of effort. Consider Equation 4.23, which is the same as Equation 4.13a above.

$$\left[P y_E - C'\right] = e^{\delta t}\lambda(t) y_E \tag{4.23}$$

The left-hand side is the marginal gain in profit for a change in effort, given the existing stock size. It is analogous to the marginal profit used in analyzing the static case in Chapter 2 (see Figure 2.7b and Equation 2.18). The difference is that here we are talking about marginal profits with a given stock size and above we were talking about marginal sustainable profits.

In order to maximize *current profits*, annual effort should be adjusted until marginal profit equals zero. As long as increasing effort is adding more to current revenues than it is adding to current costs, profits will increase. But maximizing the NPV of profits is different from maximizing current profits, and accordingly the necessary condition is not to set current marginal net revenue equal to zero. Since the right-hand side of the expression is positive, then in order to maximize NPV, in any period it is necessary to hold the production of effort to a level less than that which would maximize current profits.

Consider the right-hand side in more detail. The term $e^{\delta t}\lambda(t)$ is the current value of a unit of stock in the ocean at time t. The term y_E is the amount of yield that will be produced by the marginal unit of effort. Therefore, the whole expression represents the reduction in the value of fish in the sea as a result of increasing effort and can be thought of as the user cost of a unit of effort. It shows what future values are foregone by increasing effort in any period. In other words, in order to maximize the NPV of profits, effort in each period must be increased until the marginal current profit is just equal to the value of the forgone future profits. It is necessary to take into account how current effort will affect the tradeoff between current profit and the NPV of profit over time.

4.4.1.1 Optimal trajectory curves: Case 1

While the various forms of Equation 4.13 can help explain the concept of how to select the level of effort over time, operationally it is not very useful unless the time path of $\lambda(t)$ is known. Unfortunately, it cannot be derived independently; it can be obtained only as a part of the general solution to the Hamiltonian problem. How this can be finessed is explained in the exercises given in the CD.

But for now, consider the details of the optimal path in terms of combinations of effort and stock size as the fishery is operated so as to maximize the PV of net revenues. The nature of the path will depend on the initial stock size relative to the long-run optimal stock size. To repeat, the problem is to determine how much effort should be applied for a given stock size. The size of the fleet is an important consideration because it is a potential limit on what can be produced (see the constraints listed under Equation 4.11). Figure 4.5 is the same as Figure 4.1, except an open access trajectory starting with an unexploited stock, and two optimal time paths have been added. The optimal trajectories were derived using the algorithm described in the exercises for this chapter. Point B on the PEC represents the stationary dynamically optimal combination of effort and stock size. That stock is obtained by solving Equation 4.16 above assuming the discount rate is 12%. The level of effort is the one that will have catch equal to growth at that stock size.

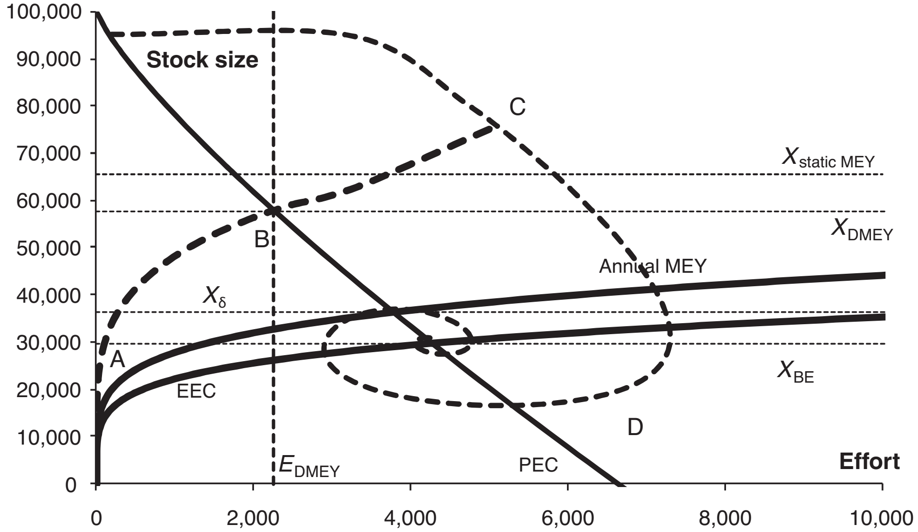

Figure 4.5 Optimal path in terms of combinations of effort and stock size.

The optimal path to point B, if the initial stock size is 20,000, is demonstrated by the path AB. Note that at all points it is to the left of the annual MEY curve, because at any stock size on the optimal path, the level of effort must be less than that which maximizes current profits for that period. Effort is initially kept very low in order to let the stock grow rapidly. As stock grows, effort is gradually increased, but it is always kept low enough such that catch is less than growth, so the stock will continue to grow until it reaches the long-run optimal size. At the stationary equilibrium, effort will reach a level where catch will equal growth. It is interesting to note that if the initial stock size is anywhere between 20,000 and X_{DMEY}, the optimal path will be coterminous with path AB.

The line CB shows the optimal trajectory for the case when the initial stock is 70,000, and the stock needs to be reduced to get to the stationary optimum. Effort starts out relatively high so as to push the stock down, but eventually decreases as the stock falls to the optimal level such that catch is equal to growth.

The situation is a little more complex for higher stock sizes. For example, if the initial stock size is 100,000 the optimal trajectory, when effort is not constrained, calls for a very large amount of effort in the first period. This pushes the stock to a very low level. After that, the optimal trajectory looks something like AB where the stock is gradually rebuilt. The logic of this is easy to see. It makes sense to have large net revenue early on when there is no discounting and then have lower net revenue in later periods when discounting means that they will have a lower PV. In addition, because of the marginal productivity of stock at higher stock sizes, it takes less effort to take a given level of harvest.

While the economics of this rapid depletion are clear, it is necessary to add a touch of reality to the analysis. For one thing, this deterministic model ignores the possibility that pushing the stock to low levels can have serious side effects in terms of stock failure that is likely to exist in a real-world fishery. For another, in reality there are constraints on the amount of effort that can be produced. These limits are often related to the history of exploitation of a fish stock. The paradoxical thing is that if an open access fishery pushes the stock to a low level, the optimal correction would call for very little effort early on. However, there will likely be a relatively large fleet, some of which must be kept idle to allow the stock to grow. On the other hand, in the opposite (but likely rare in today's world) case of a developing fishery, there may not be very large fleet. The appropriate balance is to build the fleet such that it can adjust to be a match for the optimal stock size within a reasonable amount of time, but still be large enough to take advantage of the early large stocks. This is a very complex problem even in the abstract (see Clark et al., 1979).

In contrast to this analysis, the bang-bang approach, which follows from the linear model, would call for zero effort when starting at a low stock size until X_{DMEY} is achieved.

4.4.1.2 Optimal trajectory curves: Case 2

The solution of Equation 4.21 provides a nominal solution for the dynamic optimal stock size in the Case 2 situation. It is depicted in Figure 4.6 and labeled X_{DMEY}. Given the parameters of the Schaefer function and a 12% discount rate, the dynamic optimal stock size is 30,000 tons. While 12% is a high discount rate, it was selected for the convenience of modeling. The level of effort where catch equals growth for this optimal stock size is indicated at E_{DMEY}.

We can now explain when the nominal solution will in fact be the correct one. It depends on the relative sizes of E_{MEY} and E_{DMEY} and the initial stock

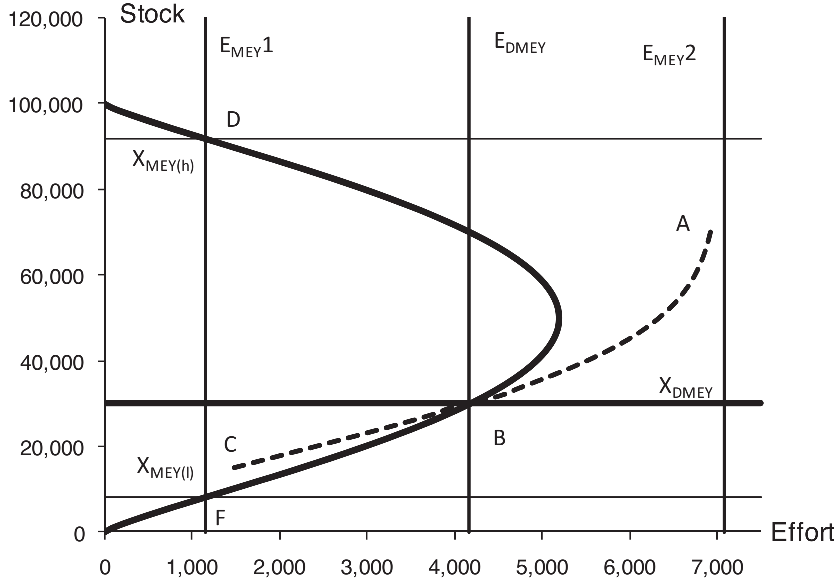

Figure 4.6 Optimal paths when harvest is not a function of stock size.

size. Recall that E_{MEY} is the level of effort that will maximize short-run profits and it is independent of stock size (see Equation 4.9b). If the price–cost ratio is such that E_{MEY} is to the left of E_{DMEY}, the nominal solution will not be valid (see $E_{\mathrm{MEY}}1$). This is because it never makes sense to produce more effort than E_{MEY}. The higher levels of effort will lower net revenues, no matter what the stock size. It does not pay to invest in the stock.

In this case, the actual optimal stock size depends on the initial stock size. If the initial stock size is greater than $X_{\mathrm{MEY}(l)}$, the optimum stock size will be $X_{\mathrm{MEY}(h)}$. No matter where the stock is in this range, it makes sense to maximize current profits by operating at E_{MEY}. If the stock size is less than $X_{\mathrm{MEY}(h)}$, catch will be less than growth and the stock size will increase. On the other hand, if stock size is greater than $X_{\mathrm{MEY}(h)}$, the reverse will be true. In either case, the trajectory will be a straight line at E_{MEY}, moving up or down depending on the initial stock size.

The change in stock size is an indirect effect of maximizing current profits. There is no intended investment in the stock per se, because higher stock sizes will not increase current or future profits. It would not make sense to move to X_{DMEY} by operating at E_{DMEY}, even though that is what Equation 4.21 calls for because profits would be lower there.

On the other hand, if the initial stock is less than $X_{\mathrm{MEY}(l)}$, it becomes the optimal stock size. The optimal trajectory will lie just to the left of the PEC, depending on the exact initial stock size. Over this range of stock sizes, operating at $E_{\mathrm{MEY}}1$ will generate a catch that is greater than growth and the stock will eventually collapse. Therefore, in order to maintain the stock, it is necessary to operate at a lower level of effort and allow the stock to grow. The trajectory must lie within the PEC. In this case, it is necessary to forgo some current profits in order to have a permanent stream of future profits. The optimal trajectory will hit the PEC at the stock effort combination of $X_{\mathrm{MEY}(l)}$ and E_{MEY}. That stock size will be maintained because catch will equal growth. But why not let the stock grow to $X_{\mathrm{MEY}(h)}$? The technical answer is that doing so would not maximize the NPV of output. Once the stock reaches $X_{\mathrm{MEY}(l)}$, and E reaches E_{MEY}, it would take a decrease in effort to get the stock to grow. That would decrease profits in the current period but not add anything to future profits.

As the price–cost ratio increases, the E_{MEY} curve shifts to the right. In those instances where it is to the right of the PEC, the solution to Equation 4.21 is valid (see $E_{\mathrm{MEY}}2$). The PEC does not intersect the EEC, and so there is nothing equivalent to $X_{\mathrm{MEY}(l)}$ and $X_{\mathrm{MEY}(h)}$.

In this case, the optimal stock size is X_{DMEY}, the stock size where the slope of the growth curve is equal to the discount rate. The optimal trajectories are similar to those in Figure 4.5. When the initial stock size is greater than X_{DMEY}, the optimal trajectory will be somewhere along AB, depending on the exact initial stock size. Likewise, CB is the optimal trajectory when the initial stock size is less than X_{DMEY}. Note that AB is everywhere outside of the PEC, and at those combinations of E and X growth is less than catch and the stock size will fall. The reverse situation holds at all points along CB.

On either trajectory, effort will always be less than $E_{\mathrm{MEY}}2$, where current profits are maximized. The distance between $E_{\mathrm{MEY}}2$ and the trajectory is related to the size of the shadow value of the stock (see Equation 4.23). At high stock sizes, user cost of a unit of effort is low, and so fishing effort and catch can be high. Initially, effort is close to $E_{\mathrm{MEY}}2$. Although stock size will fall, current profits are higher than the decrease in the PV of future profits. On the other hand, at low stock sizes, the user cost of effort is high. Effort should be kept low to allow the stock size to grow. The user cost of effort decreases along the CB trajectory as the fish in the sea become relatively more abundant.

An in-between case where the E_{MEY} curve intersects the PEC to the right of E_{DMEY} is discussed in the exercises given in the CD. The results are a combination of the previous two cases.

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Suggested Reading

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Chapter 5

Age-structured bioeconomic model

5.1 Introduction

The previous chapters have presented the basic theory of fisheries bioeconomics in terms of the Schaefer logistic growth biological model. It is a simple biological model, but one that is still applied to analyze some real-world fisheries because of the relative ease of obtaining the required data. It is also useful for analytical purposes because it allows for easy mathematical manipulation and a straightforward transition into simulation modeling. It captures the basics of stock size change with and without fishing mortality. As such it provides a valuable platform for demonstrating the dynamics of open access, optimal, and regulated utilization.

In the Schaefer model, the net effects of recruitment of new individuals and the growth and natural mortality of existing individuals are all captured in a simple equation. Further, when considering fishing mortality, it is implicitly assumed that natural and fishing mortality can be considered independently when tracking changes in stock size over time.

Although it is more complicated, a better picture of population dynamics can be obtained by using an age-structured format where recruitment, individual growth, and natural mortality are treated independently. The purpose of this chapter is to explain how age-structured models work and to show how they can be introduced into a bioeconomic model that is analogous to those described above. For the most part, the economic and fishery management lessons that follow from the Schaefer model can be stated in terms of the age-structured model. In fact, although it requires numerical rather than analytical techniques, it is possible to derive sustainable revenue and cost curves as well as population equilibrium and economic equilibrium curves (PEC and EEC). It does provide something extra in that it allows for the analysis of age at first capture regulations and for the peculiarities of different stock–recruitment relationships. But for the most part, the purpose of introducing it is not to learn more fisheries economics per se. The purpose is to ensure that economic principles can be applied in the best possible bioeconomic model.

Looked at the other way around, it is gratifying to note that given its relative simplicity, the Schaefer model captures the basic results that follows from the age-structured model.

To set the stage, it will be useful to explain the basic differences between the Schaefer and the age-class model and to introduce some definitions. In the Schaefer model, the biological state variable is stock biomass and X is a scalar. Biological equilibrium occurs when catch is equal to growth and stock size does not change.

In the age-class model, the equivalent of the state variable must be described as a vector. The vector is the number of individuals in each of the age classes. This can be defined as the *age-class profile* (ACP):

$$\mathrm{ACP} = \{N_0, N_1, N_2, \ldots, N_k\} \tag{5.1}$$

N_i is the number of individuals in the k different age classes. It is also useful to describe the ACP in terms of different biomass measures. The biomass at age, call it X_i, is simply the number of individuals times the average weight at age, w_i. The biomass ACP is:

$$\begin{aligned}\text{Biomass ACP} &= \{N_0 w_0, N_1 w_1, N_2 w_2, \ldots, N_k w_k\}\\ &= \{X_0, X_1, X_2, \ldots, X_k\}\end{aligned} \tag{5.2}$$

Another useful measure of biomass is spawning stock biomass (SSB). SSB is a measure of the spawning potential of a particular age class. It can be thought of as the sexually mature individuals in an age class, as measured by an age-specific fecundity coefficient (s_i), but there can be different definitions depending on the peculiarities of the species involved. The SSB ACP is:

$$\begin{aligned}\text{SSB ACP} &= \{s_0 N_0 w_0, s_1 N_1 w_1, s_2 N_2 w_2, \ldots, s_k N_k w_k\}\\ &= \{s_0 X_0, s_1 X_1, s_2 X_2, \ldots, s_k X_k\}\end{aligned} \tag{5.3}$$

Although there are different ways to look at the ACP, the profile by numbers is the most basic. For definitional purposes, the term age-class profile or ACP, when used without further modification, will refer to the profile by numbers.

While a complete description of a stock requires the ACP, it is often convenient to express stock characteristics as a scalar in terms of total biomass (TB) or spawning stock biomass (SSB). The former may be more useful for potential harvest considerations, while the latter is more important for considering reproductive potential.

$$\mathrm{TB} = \sum_{i=0}^{i=k} N_i w_i = \sum_{i=0}^{i=k} X_i \tag{5.4}$$

$$\mathrm{SSB} = \sum_{i=0}^{i=k} s_i N_i w_i = \sum_{i=0}^{i=k} s_i X_i \tag{5.5}$$

It can be seen that TB and SSB are linear transformations of each other. When making general comparisons between the Schaefer and the age-class models, X is analogous to TB or SSB, but there are differences because the composition of the ACPs can be as important as the total values. A very important point is that while a particular ACP will generate a specific TB or SSB, there are many ACPs that will generate a particular TB or SSB.

Because harvest is composed of the number of individuals in the different age classes that are taken in any year, it is also necessary to use vectors to measure catch. The catch ACP is a vector, the elements of which represent the *number* of individuals that are harvested from each age class. The catch ACP is a function of the ACP in numbers and the amount of aggregate effort applied. The equation for calculating the elements of this vector will be derived and discussed below (see Equation 5.22).

$$\text{Catch ACP} = \{Y_0(N_0),\ Y_1(N_1),\ Y_2(N_2),\ \ldots,\ Y_k(N_k)\} \tag{5.6}$$

It should be pointed out that age-specific catch is also a function of effort, and age-specific catchability and natural mortality. This will be introduced below.

It follows that the biomass catch ACP and total harvest can be represented as:

$$\text{Biomass catch ACP} = \{w_0 Y_0(N_0),\ w_1 Y_1(N_1),\ w_2 Y_2(N_2),\ \ldots,\ w_k Y_k(N_k)\} \tag{5.7}$$

$$\text{Total harvest} = \sum_{i=0}^{i=k} Y_i(N_i) w_i \tag{5.8}$$

Further assuming the price can vary, depending on the age and size of the individual, and P_i is the age class-specific price, then total revenue is:

$$\text{Total revenue} = \sum_{i=0}^{i=k} P_i Y_i(N_i) w_i \tag{5.9}$$

The explanation of a biological equilibrium in the age-class model is more complex than in the Schaefer model. It is more than having a constant SSB, although that is part of it. An equilibrium also requires that the elements of the ACP vector do not change. This will, of course, generate a constant SSB. But it is the constant ACP that guarantees the constant SSB, not the other way round.

To follow the dynamics of a fish stock, it is necessary to track the changes in each of the elements in the ACP vector. While it amounts to the same thing as comparing catch and growth in the Schaefer model, it is considerably more complex. While "catch equals growth" is the equilibrium condition in the Schaefer model, it is not possible to state the conditions that will yield an equilibrium in the age-class model until the fine points have been described in more detail.

5.2 The age-class bioeconomic model

To set the stage, consider the equations for the dynamics of the disaggregated Schaefer model in Chapter 3 (See Equations 3.26 and 3.27, which for convenience are reproduced here):

$$X_{t+1} = X_t + G(X_t) - qE_tX_t \tag{3.26}$$

$$V_{t+1} = V_t + \varphi_1\pi_t \tag{3.27}$$

The first equation shows the change in stock size while the second shows the change in fleet size. Stock size is measured in terms of biomass as a scalar. The change in stock size depends on the additions from growth and the subtractions due to catch. Growth is a function of stock size. Catch is the product of the catchability coefficient, stock size, and total effort. Total effort depends on the number of boats, the vessel effort per day, and the number of days fished. That is, $E_t = V_t f^*(X_t)D_{\max}$. Recall that the product of effort and the catchability coefficient is the fishing mortality rate. $F_t = qE_t$. It is the portion of the stock that is taken by fishing in any period. In the age-class model, it is necessary to look at age-specific fishing mortality rates rather than a general stock wide fishing mortality rate. But the same principle applies. The age-specific fishing mortality rate is the product of effort and the age-specific catchability coefficient. This is explained in more detail below (see the discussion of Equation 5.20).

The change in fleet size depends on the level of per vessel profits, which is a function of fish price, the cost of effort, total catch, and the number of vessels. Except for price and cost, these elements are contained in the stock change equation.

The age-class bioeconomic model does exactly the same thing as is accomplished by these two equations, except that for reasons explained below, tracking biomass requires a series of computations rather than a single equation. Tracking the change in fleet size is effectively the same in both models.

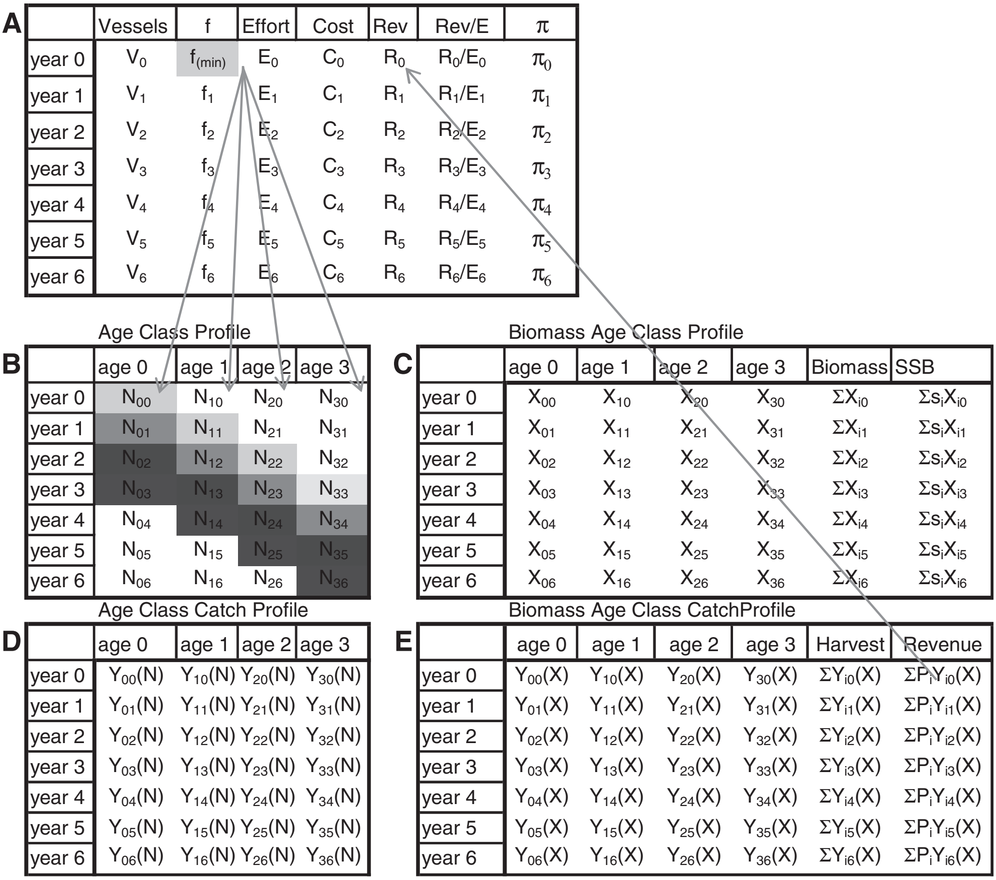
As with the previous chapters, a simulation model will be constructed as a companion to the discussion. It will prove useful to use a heuristic form of this model as a framework for explaining the basics of age-class models (see Figure 5.1). (For simplicity, the number of age classes is arbitrarily set at 4.) This will serve a double purpose. First, it provides a way to clearly explain the connections and interrelationships in what is a very complicated process. Second, it describes the flow diagram of the actual age-structured simulation model that will be used in the exercises to this chapter.

The details of the biological tracking process analogous to Equation 3.26 can be explained using the bottom four panels of Figure 5.1. The bioeconomic model can be completed by using Part A, which is basically the same as the simulation model developed in the Schaefer model, and showing how it is related through input and output to the other parts. The differences relate to the complexities of the more complete biological model. Parts B, C, D, and E describe the age-class analysis strictly from the biological point of view. Part B describes age classes by number while Part C shows the corresponding age class by weight along with summations described above. Parts D and E show catch at age by number and weight, respectively.

The fundamental working of the age-class model is described in Part B. Each row is the age-class profile for a given year. The first subscript refers to the age-class number and the second refers to the year number. The basic question is, given an initial age-class profile, how does the ACP change over time?

A useful way to begin to answer this question is to introduce the concept of the cohort and the cohort diagonal. The *cohort* for any year is the number of individuals that are recruited to the first age class. The cohort diagonal traces how the numbers at age will change as the cohort passes through the population. The cohort diagonals for age classes 0–4 are indicated in Part B in different shades of gray. (Note that subtracting the age class subscript from the year subscript will always give the birth year of the cohort.) The vector for the cohort diagonal for any age i and year t can be represented as:

$$CD = \left\{N_{it},\ N_{i+1,t+1},\ N_{i+2,t+2},\ \ldots,\ N_{i+k,t+k}\right\} \tag{5.10}$$



A

	Vessels	f	Effort	Cost	Rev	Rev/E	π
year 0	V_0	$f_{(min)}$	E_0	C_0	R_0	R_0/E_0	π_0
year 1	V_1	f_1	E_1	C_1	R_1	R_1/E_1	π_1
year 2	V_2	f_2	E_2	C_2	R_2	R_2/E_2	π_2
year 3	V_3	f_3	E_3	C_3	R_3	R_3/E_3	π_3
year 4	V_4	f_4	E_4	C_4	R_4	R_4/E_4	π_4
year 5	V_5	f_5	E_5	C_5	R_5	R_5/E_5	π_5
year 6	V_6	f_6	E_6	C_6	R_6	R_6/E_6	π_6

Age Class Profile

B

	age 0	age 1	age 2	age 3
year 0	N_{00}	N_{10}	N_{20}	N_{30}
year 1	N_{01}	N_{11}	N_{21}	N_{31}
year 2	N_{02}	N_{12}	N_{22}	N_{32}
year 3	N_{03}	N_{13}	N_{23}	N_{33}
year 4	N_{04}	N_{14}	N_{24}	N_{34}
year 5	N_{05}	N_{15}	N_{25}	N_{35}
year 6	N_{06}	N_{16}	N_{26}	N_{36}

Biomass Age Class Profile

C

	age 0	age 1	age 2	age 3	Biomass	SSB
year 0	X_{00}	X_{10}	X_{20}	X_{30}	ΣX_{i0}	$\Sigma s_i X_{i0}$
year 1	X_{01}	X_{11}	X_{21}	X_{31}	ΣX_{i1}	$\Sigma s_i X_{i1}$
year 2	X_{02}	X_{12}	X_{22}	X_{32}	ΣX_{i2}	$\Sigma s_i X_{i2}$
year 3	X_{03}	X_{13}	X_{23}	X_{33}	ΣX_{i3}	$\Sigma s_i X_{i3}$
year 4	X_{04}	X_{14}	X_{24}	X_{34}	ΣX_{i4}	$\Sigma s_i X_{i4}$
year 5	X_{05}	X_{15}	X_{25}	X_{35}	ΣX_{i5}	$\Sigma s_i X_{i5}$
year 6	X_{06}	X_{16}	X_{26}	X_{36}	ΣX_{i6}	$\Sigma s_i X_{i6}$

Age Class Catch Profile

D

	age 0	age 1	age 2	age 3
year 0	$Y_{00}(N)$	$Y_{10}(N)$	$Y_{20}(N)$	$Y_{30}(N)$
year 1	$Y_{01}(N)$	$Y_{11}(N)$	$Y_{21}(N)$	$Y_{31}(N)$
year 2	$Y_{02}(N)$	$Y_{12}(N)$	$Y_{22}(N)$	$Y_{32}(N)$
year 3	$Y_{03}(N)$	$Y_{13}(N)$	$Y_{23}(N)$	$Y_{33}(N)$
year 4	$Y_{04}(N)$	$Y_{14}(N)$	$Y_{24}(N)$	$Y_{34}(N)$
year 5	$Y_{05}(N)$	$Y_{15}(N)$	$Y_{25}(N)$	$Y_{35}(N)$
year 6	$Y_{06}(N)$	$Y_{16}(N)$	$Y_{26}(N)$	$Y_{36}(N)$

Biomass Age Class CatchProfile

E

	age 0	age 1	age 2	age 3	Harvest	Revenue
year 0	$Y_{00}(X)$	$Y_{10}(X)$	$Y_{20}(X)$	$Y_{30}(X)$	$\Sigma Y_{i0}(X)$	$\Sigma P_i Y_{i0}(X)$
year 1	$Y_{01}(X)$	$Y_{11}(X)$	$Y_{21}(X)$	$Y_{31}(X)$	$\Sigma Y_{i1}(X)$	$\Sigma P_i Y_{i1}(X)$
year 2	$Y_{02}(X)$	$Y_{12}(X)$	$Y_{22}(X)$	$Y_{32}(X)$	$\Sigma Y_{i2}(X)$	$\Sigma P_i Y_{i2}(X)$
year 3	$Y_{03}(X)$	$Y_{13}(X)$	$Y_{23}(X)$	$Y_{33}(X)$	$\Sigma Y_{i3}(X)$	$\Sigma P_i Y_{i3}(X)$
year 4	$Y_{04}(X)$	$Y_{14}(X)$	$Y_{24}(X)$	$Y_{34}(X)$	$\Sigma Y_{i4}(X)$	$\Sigma P_i Y_{i4}(X)$
year 5	$Y_{05}(X)$	$Y_{15}(X)$	$Y_{25}(X)$	$Y_{35}(X)$	$\Sigma Y_{i5}(X)$	$\Sigma P_i Y_{i5}(X)$
year 6	$Y_{06}(X)$	$Y_{16}(X)$	$Y_{26}(X)$	$Y_{36}(X)$	$\Sigma Y_{i6}(X)$	$\Sigma P_i Y_{i6}(X)$

Figure 5.1 Economic variables and age-class profiles over time for population, biomass, and catch.

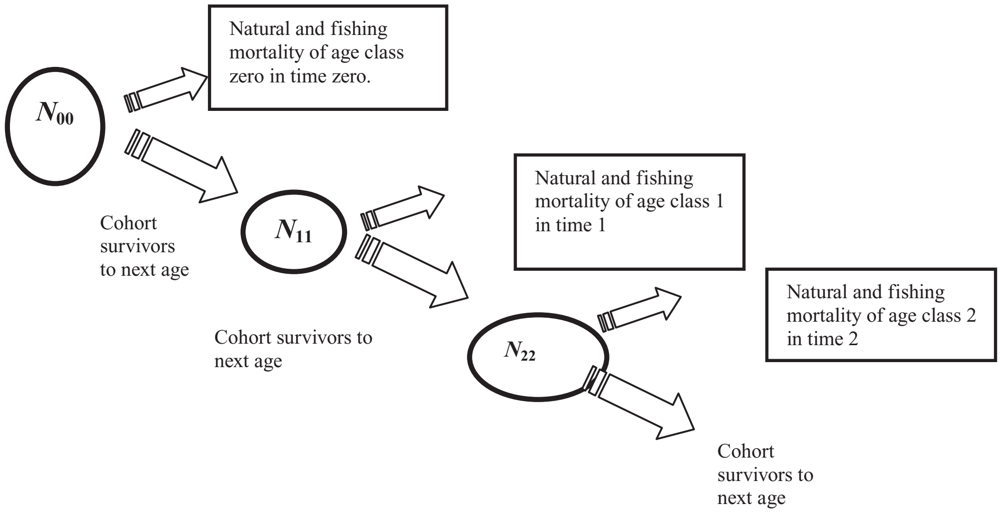


Figure 5.2 Dynamics of age cohort survival.

At this point, it may be useful to pause and emphasize the difference between the ACP and the cohort diagonal. The ACP is a row in the grid that shows the numbers at age at a given point in time. The cohort diagonal is a diagonal in the grid that shows the number of remaining individuals that survive both natural and fishing mortality as a cohort grows older. The analytics of the cohort diagonal can be explained in more detail using Figure 5.2. The number of 1-year-old fish in period 1 will be the survivors of 0-year-old fish in period 0 after taking into account both natural and fishing mortality. To generalize, in any time period, if the natural and fishing mortality rates are known, the value in any cell in Part B can be calculated from the value in the cell diagonally up and to the left. The exact calculation procedure will be explained below.

Before moving on, consider the ACP for year 3. It is composed of individuals from the cohorts from years 0 to 3. For example, N_{33}, the number of individuals in age class 3, is the surviving members of the cohort from year 0. It can be seen that the ACP at any time is the result of recruitment and natural and fishing mortalities over the previous years. It follows that any desired changes in the ACP can only be accomplished over time. Given the diagram, this is an obvious point, but it is one that is critical to understanding stock population dynamics, especially as it applies to fisheries management.

Return now to the discussion of tracking the changes in the set of ACPs of a fish stock over time. There are two separate issues involved. One is what proportion of each age class will survive to the next period. This question is answered by the cohort diagonal. The other is how many individuals will be "recruited" into the zero age class or the young of the year age class.

The answer to the second question depends on the reproductive capacity of the fish stock. This is a very complicated topic, and at this juncture, it is necessary to assume the existence of a recruitment function which shows the number of recruits that will be added to zero age class in the next period as a function of the SSB, as defined above. Different types of recruitment functions will be explained in the next section, and how they affect the overall population dynamics will be explained in the later sections of this chapter. It should be stressed that it is very difficult, if not impossible, to estimate a recruitment function in all cases. Even if it is possible, the dispersion around the point estimates is often quite high.

Now consider Part C of Figure 5.1. It shows the biomass ACP for each year which corresponds to the ACP for the same year in Part B (see Equation 5.2). The total biomass and the SSB are also shown. The relationship between Parts B and C is that the SSB follows from the ACP in any year. And from the other way around, the number of recruits to age class zero in any year is related to the SSB of the previous year. That is, the element N_{0t} in Part B follows from $\sum s_i X_{i,t\text{-}1}$ in Part C.

In summary, in each year the size of the age zero year class is determined by recruitment, which is normally related to the size of the SSB. The size of any other age class can be determined by noting how the previous age class the year before is changed because of fishing and natural mortality. It should be clear that the amount of fishing mortality is an important driver that determines how the size and composition of the stock will change over time.

Parts D and E track the catch in numbers and weight over time. The values can be calculated from the information in Parts B and C and the parameters used to calculate it. To state the obvious, there are two sources of mortality: natural mortality and fishing mortality. Part B tracks how the numbers at age change as a result of both types of mortality. It is a simple matter to calculate total mortality for any age class for any time period using numbers given in the tables. For example, the total mortality to age class 2 in period 1 can be calculated by taking the difference between N_{21} and N_{32}. That is, if there are 1,000 individuals in age class 2 in year 1 and 800 individuals in age class 3 in year 2, the total mortality for age class 2 in year 1 was 200 individuals. Harvest will be some fraction of this total amount. The fraction can be calculated using the ratio of the fishing mortality rate to the sum of the natural and fishing mortality rates. The catch in numbers can be converted to catch in weight in Part E using the weight at age coefficients. Finally, using data on price at age, it is possible to calculate the revenue that will be earned each year.

Before going on to show how Part A can be connected to the biological parts of the age-class model, it will be useful to show what this model is capable of doing from a pure biological point of view. The control variable of the biological model is the fishing mortality rate. Assuming the other relevant parameters are known, the model can be used to estimate what will happen to stock size and harvest levels over time for different fishing mortality rates. When used in this manner, the simulation program is sometimes call a stock projection model. It is also possible to look at things from the other way around. For example, the model can be used to calculate the fishing mortality rates that will achieve a desired harvest level. Given that rate, it will also be possible to see how that harvest level will affect total stock size and future recruitment. The model can also be used to calculate the necessary fishing mortality rates to achieve a stock recovery goal. For example, if the goal is to achieve a 25% increase in SSB in a

10-year period, it would be a relatively simple task to use the model to calculate several different time paths of fishing mortality rates that will achieve the goal.

Part A completes the bioeconomic model. Actually by itself, it is very similar to the more simple simulation models used above (see the exercises to Chapter 2 given in the CD). In those cases, the change in stock size could be tracked in one column using Equation 3.26. In the age-class model, it is necessary to use Parts B, C, D, and E to complete this task. Part A tracks how individual vessels operate in response to returns from fishing. This must be done in a slightly different way because there is no simple catch equation. Therefore, it is not possible to derive a vessel daily yield function. That yield function is used to derive the vessel daily profit function which can be used to calculate the profit-maximizing daily level of effort (see Equations 3.11a–3.13). The basis of that analysis is that the vessel is able to calculate a return per unit of effort based on the current stock size. This is calculated as PqX. Given the complexity of measuring catch in an age-class model (see below), it is not possible to make such an a priori calculation. The issue can be finessed, however, by assuming that vessel operators use the average return per unit of effort in the previous period to calculate the optimum level of effort in the current period. That is, Equation 3.13 must be recast as:

$$f_t = \frac{(R_{t-1}/E_{t-1}) - c_i}{2c_s} \tag{5.11}$$

This means that it is necessary to set an initial value for f_0, the daily level of effort in period 0. For purposes here, it will be set at $f_{\min}$, the level of daily effort at the minimum of the daily average cost curve. In other words, the amount of effort that is produced in any year after year 0, the variable in the second column of Part A, will be a function of revenue per unit of effort in the previous year. Revenue per unit of effort is the variable in the fifth column of Part A.

The bioeconomic interrelationships work as follows. Given an initial fleet size and the assumed initial level of f, it is possible to calculate E_0, the total effort produced in the initial period. The fishing mortality rate for each age class in that period is the product of E_0 and the age-class catchability coefficient. Using the calculations described below, with these fishing mortality rates, it is possible to calculate how the size of each age class will change from year 0 to year 1. This will also give the catch levels and revenue of year 0 (see arrows emanating from E_0 indicating its effects on the entire ACP next year; see also the Revenue column in Part E and the arrows connecting R_0 that flows from that harvest to the Rev column in Part A, which determines fleet size in period 1). This completes the connection between the economic sector in Part A and the stock growth component in the other four parts.

The chain of logic in Part A can be summarized as follows. Daily effort in any period is a function of revenue per unit of effort in the previous period. Total effort is a function of the existing fleet size and the season length. This total effort determines the total landings and revenue for the period as well as the change in ACP for the next period. The fleet size next year will depend on the profits that result from the periodic catch.

5.3 The details of the age-class bioeconomic model

5.3.1 Functions and parameters

5.3.1.1 Weight at age

Individual growth is a function of food availability, water temperature, and species metabolism rates. Sometimes, these can change because of environmental conditions or stress from fishing pressure.

There are two ways of obtaining the weight at age coefficients. One is where samples of individual fish taken from actual commercial harvest or research cruises are aged and average weights are obtained. Fish can be aged by counting the rings in an ear bone called the otolith in much the same way that trees can be aged by counting rings from a core sample from the trunk.

If it is not possible to obtain sufficient samples of all age classes, it is sometimes possible to estimate length and weight growth equations. Length at age can be calculated using the well-known von Bertalanffy growth formula:

$$L_i = L_\infty \left[1 - e^{-k(i-i_0)}\right] \tag{5.12}$$

where L_∞ is the maximum length of the species, k is the curvature parameter, and i_0 is the adjustment parameter of the growth function. Age-specific weight, w_i, is estimated by the following length–weight relationship where a_3 and b_3 are constants:

$$w_i = a_3 L_i^{b3} \tag{5.13}$$

There are standard methods of estimating the parameters of these equations (see Ricker, 1975; Sparre *et al.*, 1989).

5.3.1.2 Recruitment

Recruitment of new individuals is one of the most critical, least understood, and most difficult to estimate process in fish population dynamics. Recruitment is a function of (1) the size of spawning stock during the seasonal reproductive period, (2) the age-specific average fecundity of females, (3) the duration of planktonic life during the larval stages, (4) the environmental conditions prevailing during the planktonic life, (5) the habitat and food availability conditions when settlement or autonomous movement in the water column occurs in postlarval stages, and (6) the density of predators in space and time, from spawning to postlarval stages. In the case of sedentary species, stock density in settlement grounds is also a fundamental factor determining recruitment success over time.

There are different hypotheses concerning how the number of recruits varies with the size of the SSB, and some apply better for particular species than others. Four types of recruitment functions will be considered here: constant recruitment, Beverton–Holt asymptotic recruitment, the Ricker density-dependent recruitment, and depensation recruitment. The representative shapes of these

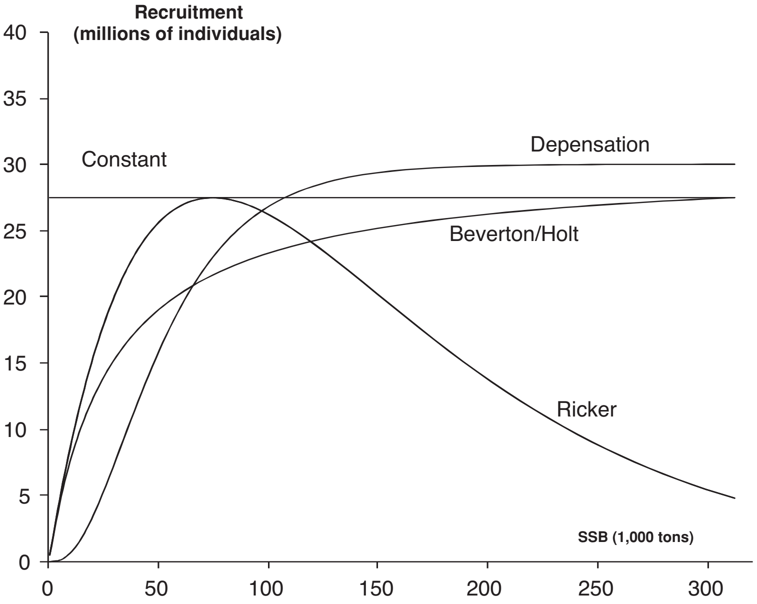


Figure 5.3 Alternative stock–recruitment relationships.

functional forms can be seen in Figure 5.3 (see Beverton and Holt, 1957; Caddy, 1975; Ricker, 1975; Cushing, 1981; Gulland, 1983; Hilborn and Walters, 1992). The equations for these functions as well as the parameter values that are used in the model are shown in Table 5.1.

The Beverton–Holt function is an asymptotic curve exhibiting constant recruitment beyond a certain stock density. It implies an arithmetically progressive reduction in the recruitment rate as stock density increases. The Beverton–Holt

Table 5.1 Alternative functional forms of recruitment processes

Equation	Values
Constant	
$R = R_C$	
R_C	27,500,000
Beverton-Holt:	
$R = \alpha_{bh}$ SSB/$[X_{sp} + \beta_{bh}]$	
α_{bh}	30,000,000
β_{bh}	28,955
Ricker:	
$R = \alpha_r$ SSB $e^{-[\beta_r \mathrm{SSB}]}$	
α_r	1,000
β_r	0.000013
Depensation	
$R = \alpha_d$ (1 - $\mathrm{e}^{-[\beta_d \mathrm{SSB}]})^3$	
α_d	30,000,000
β_d	0.000033

function is applicable when recruit abundance is limited by available food or habitat, or when a predator continually adjusts its own attack rate to changes in prey abundance. In the equation, α_{bh} is the maximum possible number of recruits and β_{bh} is the SSB needed to produce (on average) $\alpha_{bh}/2$ recruits.

The Ricker function applies when strong density-dependent mechanisms operate to restrict recruitment at larger stock sizes. The examples of density-dependent mechanisms include passive predation by adults on the postlarvae, as in the case of sandy beaches bivalve mollusks and other sedentary species; cannibalism by adults on the fry, as in some cod stocks, and in trout; increases in density of larvae, meaning that they remain longer in a vulnerable stage; and existence of time lags in the response of a predator to its prey's abundance so that a high initial density attracts more predators without allowing for subsequent reduction of prey through exploitation. In this function, α_r is the recruit per spawner at low stock sizes, and βr describes the rate at which the recruit per spawner drops as the SSB increases.

The depensation recruitment function has very low recruitment for low levels of SSB. However, over the relevant range the recruitment rate starts to increase at an increasing rate and then the rate of increase slows down and recruitment reaches an asymptote.

Quite frankly, it is often very difficult to estimate a recruitment function for a particular stock due to data limitations or due to the fact that there are many other variables besides stock size which influence recruitment. For example, in some cases, environmental conditions such as the availability of food for postlarvae are more important than the actual number of postlarvae produced. For this reason, it is sometimes useful to use a constant recruitment where the constant amount is some updated average of past recruitment.

The type of recruitment function can have important effects on the dynamics of a fish stock with or without fishing mortality. The four curves shown in the figure will be used in the examples to follow. The parameters have been selected such that the different functions are all compatible with the other parameters in the model, which will allow for some limited comparisons. For example, the maximum recruitment for all curves is very close to being the same. While the recruitment functions are clearly an important contributor to explaining the overall population dynamics of a exploited fish stock, other things such as age-specific natural mortality coefficients have important effects. As will be seen below, it is hard to predict relative equilibrium stock sizes by only considering the shape and position of the recruitment function.

5.3.1.3 Natural mortality

Natural mortality of individuals in a population is one of the most sensitive parameters in the population dynamics of marine species. Natural mortality of marine species could be caused by a number of possible factors, the main among them being: predation, spawning stress, diseases, unfavourable environmental conditions, and lack of food and/or space. To be frank, most applied age-class models use the assumption that natural mortality is the same for all age classes,

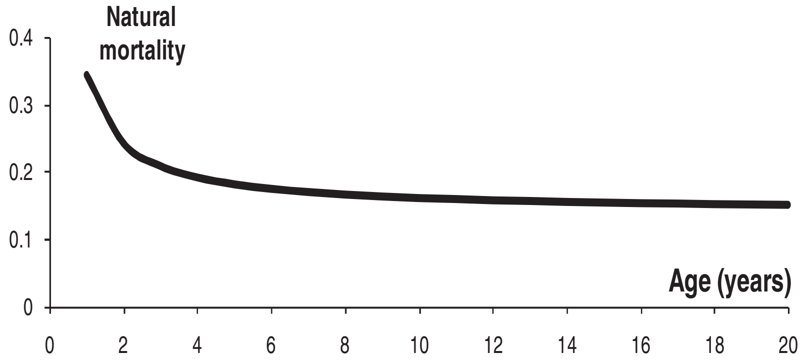


Figure 5.4 Age-specific natural mortality.

and it is frequently set equal to 0.2. However, it makes sense that there would be relatively higher natural mortalities in early stages of the life cycle because postlarvae and juveniles are more vulnerable to predation, competition, and adverse environmental conditions than adult individuals. Caddy (1991) developed a reciprocal function for natural mortality that captures these phenomena. The importance of using age-specific natural mortality functions is highlighted by Caddy and Seijo (2002). The reciprocal natural mortality model is:

$$M_i = \alpha + \frac{\beta}{i} \tag{5.14}$$

where α and β are parameters to be estimated and i is the age. The natural mortality rate initially decreases but approaches an asymptote (see Figure 5.4).

The bioeconomic model developed for this chapter can use either constant or variable natural mortality. For the most part, the examples will use a constant natural mortality but the differences that result with variable natural mortality will be demonstrated in the exercises to this chapter given in the CD.

5.3.2 Fundamental calculations of the age-class model

There are two sets of calculations that are fundamental to using an age-class model. The first is to track the number of individuals along a cohort diagonal as a cohort grows through the various age classes over time. The second is to calculate the annual number harvested in each age class.

The purpose of this section is to explain how these calculations are made. As a starting point, it is important to note that there are certain, sometimes implicit, assumptions that are made when making these calculations. As indicated in Seijo *et al.* (1998), these assumptions are:

1. The unit stock has perfectly mixed age classes.
2. There is a homogeneous distribution of age classes.
3. There is an equal probability of capture within the distribution area, before and after applying fishing effort.

4. The growth and mortality parameters are the same for the entire area of analysis.

These assumptions do not always hold and these situations will be treated in later chapters.

Both types of calculations require the use of both natural and fishing mortality rates and before explaining the calculations per se, it will be useful to provide some background on the definition and use of these rates. A *mortality rate* is the percentage of a population that dies during a given period. Annual mortality rates are most common for everyday use. However, in fisheries it is useful to be more precise because there are two types of mortality. Fishing takes place throughout the year, and in some cases, a fish that is harvested might have died of natural causes. For this, and other reasons, in population dynamics analysis, it is common to use what are called instantaneous mortality rates. This is a somewhat difficult concept to understand, but it can be explained as follows. If a of N individuals population is subject to an instantaneous mortality rate of $Z\%$, the following will hold:

$$\frac{dN}{dt} = -ZN \tag{5.15}$$

In each "instant" or part of the time period, the population is falling such that if it were to keep the same rate for the whole period, the stock would fall by $Z\%$. For the moment, assume the number of "instants" in this time period is 100 and the initial stock size is N_0. This means that in the first instant, the stock would fall by $ZN/100$, and so at the end of the first instant, the stock size would be $N_0 - (ZN_0/100)$ or $N_0[1 - (Z/100)]$. In the second instant, the stock will still fall by $Z\%$, but the size of the stock will be less because of the mortality during the first instant. Letting $N(i)$ represent stock size at the end of the ith instant, this can be generalized to:

$$N(i) = N_0\left(1 - \frac{Z}{100}\right)^i \tag{5.16}$$

If there are 100 instants in a period, then the stock size at the end of the first period would be the stock size at the end of 100 instants.

$$N(100) = N_1 = N_0\left(1 - \frac{Z}{100}\right)^{100} \tag{5.17}$$

In this case, if the instantaneous mortality rate is equal to 0.3, then the multiplicative term $(1 - 0.3/100)^{100}$ is equal to 0.740484. This generates a period mortality rate of 0.259516. Because the fish are dying throughout the year, the 0.3 instantaneous mortality rate is applied to a reduced stock size over the year and the annual mortality rate is less than the instantaneous rate.

If the number of instants is increased until it approaches infinity, the equation for the stock size at the end of one period with an instantaneous mortality rate of $Z\%$ is obtained by integrating Equation 5.15:

$$N_1 = N_0 e^{-Z} \tag{5.18}$$

For comparison purposes, $e^{-0.3}$ equals 0.740818, which translates to an annual mortality rate of 0.259182. Any instantaneous mortality rate can be readily converted to an annual mortality rate. If Z is the instantaneous mortality rate, the annual mortality rate is equal to $(1 - e^{-Z})$. An interesting sidelight that can sometimes be confusing to novices is that it is possible to have an instantaneous mortality rate that is greater than 1. For example, an instantaneous mortality rate of 1.5 translates to an annual mortality rate of 0.77687. At any instant in time, the stock is falling at a percentage rate higher than 1, but that rate will not apply for the period as a whole because of the decrease in stock size during the period.

The reason that it is necessary to use instantaneous mortality rates for this analysis is that they are additive and annual rates are not. An age class that is simultaneously subject to instantaneous natural and fishing mortality rates of M and F, respectively, will have a total instantaneous mortality rate of $(M + F)$, which will translate to an annual total mortality rate of $1 - e^{-(F+M)}$. Taking account of natural and fishing mortality as it occurs instantly through time does away with potential double counting issues.

To see this, consider the case when a stock is subject to annual fishing and natural mortality rates of F_a and M_a, respectively. It follows that:

$$N_1 = N_0(1 - F_a)(1 - M_a) = N_0(1 - F_a - M_a + F_a M_a) \tag{5.19}$$

This translates to a total annual mortality rate of $(F_a + M_a - F_a M_a)$. The negative term is necessary to avoid double counting fish that die by harvest that would have died through natural mortality.

It is important to remember that both F and M are specific to an age class. As explained above, the natural mortalities by age class are parameters of the model. Fishing mortality by age class is a function of annual effort, which is the control variable of the model, and age-specific catchability coefficients, which are another set of parameters. To be precise:

$$F_{it} = q_i\,[V_t\, f_t\, D_{\max}] \equiv q_i E_t \tag{5.20}$$

The fishing mortality on age class i in time t is the product of total effort in time t and the age-specific catchability coefficient for age class i. The daily level of effort in any period, f_t, is calculated using Equation 5.11 above.

Using the above, it is possible to demonstrate the basic equation for tracking the number of individuals in an age class though time along the cohort diagonal. Since instantaneous mortality rates are additive, if $F_i = q_i E$ represents instantaneous fishing mortality and M represents instantaneous natural mortality, then total mortality is $q_i E + M$. It follows from Equation 5.18 that the relationship between the size of the *i*th age class in year t and the size of next older age class the following year can be expressed as:

$$N_{i+1,t+1} = N_{i,t}e^{(-(M_i+q_i E_t))} \tag{5.21}$$

The number of individuals in age class $i + 1$ in year $t + 1$ is the number of individuals in age class i in year t multiplied by the exponential function of the sum of $q_i E_t + M_i$. Note that $N_{i+1,t+1}$ is diagonally down and to the right of $N_{i,t}$ in Part B of Figure 5.1. Equation 5.21 provides the procedure to calculate the cohort diagonals.

The calculation of harvest by age class follows from the above. Given the instantaneous F and M rates, the annual total morality rate is equal to $[1 - e^{-(F_{it}+M_i)}]$. Therefore, the total mortality in numbers from cohort i in time period t can be obtained by multiplying this factor times the age class size. Harvest in numbers will be the proportion of that mortality that is due to fishing. Therefore, the harvest in numbers for an age class can be represented as:

$$Y_{it}(N) = \left(\frac{q_i E_t}{q_i E_t + M_i}\right) N_{it}[1 - e^{-(q_i E_t+M_i)}] \tag{5.22}$$

The above is the equation for the element of catch ACP vector in Equation 5.6. As noted there, the catch ACP in numbers is a function of the current ACP and a specified level of effort. Put another way, given an ACP, it is possible to construct the catch ACP for a given level of effort using Equation 5.22. Then it is a simple matter to calculate total catch in weight and total revenues using Equations 5.8 and 5.9.

5.4 Biological analysis with age class model

As with the analysis of the Schaefer model above, it will be useful to use numerical examples to demonstrate the workings of the age-class model. In addition to the parameters for the different recruitment functions, as specified in Table 5.1, the biological age-specific parameters that will be used, both in the examples in the text and in the exercises for this chapter, are shown in Table 5.2. The parameters are hypothetical but have been selected such that their relative sizes produce stable results. The symbols used in the above equations for these parameters are shown in the column headings.

Individual fish length is not a part of the model per se, but the comparisons are included in order to demonstrate the workings of size limit regulations in the exercises given in the CD. Also, the table shows the variable age-specific natural mortalities, as shown in Figure 5.4. The model used in the exercises for this chapter can also be run with constant natural mortalities. Finally, note that the age-specific price relationship is quite simple. This can be changed in the exercises given in the CD.

Table 5.2 Bioeconomic age-specific parameters

Age	Length L_i (cm)	Weight w_i (g)	Catchability coefficient q_i	Sexual maturity ratio s_i	Natural Mortality M_i, (1/year)	Price P_i, (US$)
1	16.68	71.47	0.00 000 23	0.0	0.3448	0.00
2	30.33	429.99	0.00 000 41	0.0	0.2432	0.00
3	41.51	1,102.19	0.00 000 63	0.2	0.2093	8.00
4	50.66	2,003.82	0.00 000 84	0.7	0.1924	12.00
5	58.16	3,030.97	0.00 001 04	1.0	0.1822	17.00
6	64.29	4,094.97	0.00 001 20	1.0	0.1755	17.00
7	69.31	5,131.72	0.00 001 33	1.0	0.1706	17.00
8	73.43	6,100.41	0.00 001 43	1.0	0.1670	17.00
9	76.79	6,978.70	0.00 001 51	1.0	0.1642	17.00
10	79.55	7,757.55	0.00 001 57	1.0	0.1619	17.00
11	81.81	8,436.75	0.00 001 61	1.0	0.1601	17.00
12	83.65	9,021.47	0.00 001 65	1.0	0.1585	17.00
13	85.17	9,519.83	0.00 001 68	1.0	0.1572	17.00
14	86.41	9,941.26	0.00 001 70	1.0	0.1561	17.00
15	87.42	10,295.42	0.00 001 72	1.0	0.1551	17.00
16	88.25	10,591.56	0.00 001 73	1.0	0.1543	17.00
17	88.93	10,838.21	0.00 001 75	1.0	0.1536	17.00
18	89.49	11,042.98	0.00 001 75	1.0	0.1529	17.00
19	89.94	11,212.53	0.00 001 76	1.0	0.1523	17.00
20	90.31	11,352.64	0.00 001 77	1.0	0.1518	17.00

5.4.1 Biological equilibrium analysis

To begin the discussion of population dynamics with an age-class model, it is useful to go back to the beginning and consider various equilibria. What is the equilibrium SSB when there is no fishing? What is the equilibrium stock size and harvest level for various levels of effort? What is the maximum possible sustainable yield?

In the Schaefer model, it is very easy to see the equilibrium conditions by comparing the catch and growth functions. Specifically, a biological equilibrium for a given level of effort will occur at that stock size where the short-run yield curve for that level of effort intersects the growth curve (see the exercises for Chapter 2 given in the CD). More generally, by equating the short-run yield and the growth functions, it is possible to obtain the equation for the PEC which shows the equilibrium stock size for any level of effort (see Equation 2.7). Using that function, it is possible to derive a sustainable yield function. The same concepts are possible in the more realistic age-class model but the path to obtaining them is more complex. However, as a start in understanding the population dynamics of a fish stock that is composed of many age classes each changing at different rates, it is worth venturing down that path.

As the discussion below will make clear, even if effort is held constant, it takes a long time for a fish stock to reach a biological equilibrium. In fact, such equilibria should be viewed as theoretical constructs that will likely never be reached in the real world with stochastic functions and changing values for price, cost, and the catchability coefficient. But knowledge of equilibrium conditions can be useful as a framework for understanding the stock and its management.

In the Schaefer model, an equilibrium for a given level of effort is when the stock size does not change. In the age-class model, equilibrium for a given level of effort occurs when the ACP does not change. Because of the many dimensions involved, it can be difficult to grasp exactly what this entails. In order to explain it, it will be useful to introduce the concept of the fixed parameter cohort diagonal (FPCD). Recall that the cohort diagonal shows how a cohort decreases in size due to fishing and natural mortality as it ages over time (see Equation 5.10).

The FPCD will be defined as the vector of age class sizes that results from a given combination of *E* and SSB over the lifespan of the stock. A FPCD is defined for an initial year *t* and for a given combination of *E* and *R,* where *R* is a recruitment function:

$$\mathrm{FPCD}_t\,[E,\,R(\mathrm{SSB})] = \left\{N^*{}_{0t},\,N^*{}_{1,t+1},\,N^*{}_{2,t+2},\,\ldots,\,N^*{}_{k,t+k}\right\} \tag{5.23}$$

The elements of the vector are calculated as follows:

$$N^*{}_{0t} = R_t(\mathrm{SSB}_t) \tag{5.23a}$$

$$N^*{}_{it} = R^{-(\sum_{t=0}^{t=k}(M_i+E_t q_i)}\quad \text{for } i > 0 \tag{5.23b}$$

Basically, the age class is decreased each year by the combined effects of natural and fishing mortality where fishing mortality is a function of the constant level of effort and the age-specific catchability coefficients.

It should be stressed that the FPCD is a definitional artefact. The elements exist only in the real world under restrictive conditions. But the purpose of defining it is to help in specifying equilibrium conditions. Using the concept of the fixed-parameter cohort diagonal, it is possible to clearly state the conditions for a biological equilibrium in the age-class model. Further using curves that follow from the FPCD, it is possible to graphically demonstrate the familiar equilibrium concepts.

When there is constant recruitment, an equilibrium for a given level of effort will occur when the current ACP is equivalent to the FPCD for that level of effort. Equivalence is when the elements of the FPCD vector are identical to the respective elements in the ACP vector. The ACP will not change as long as effort remains constant. The initial cohort will remain the same because of constant recruitment. The other age classes will remain the same over time because age class $i + 1$ is equal to age class *i* decreased by the sum of natural and fishing mortality with the given level of effort.

When there is a recruitment function, a biological equilibrium will occur when the current ACP is equivalent to the FPCD for that level of effort, but in addition, the SSB that is generated by that ACP (see Equations 5.3 and 5.5) will produce the specified level of recruitment. These conditions will guarantee that the ACP will not change over time.

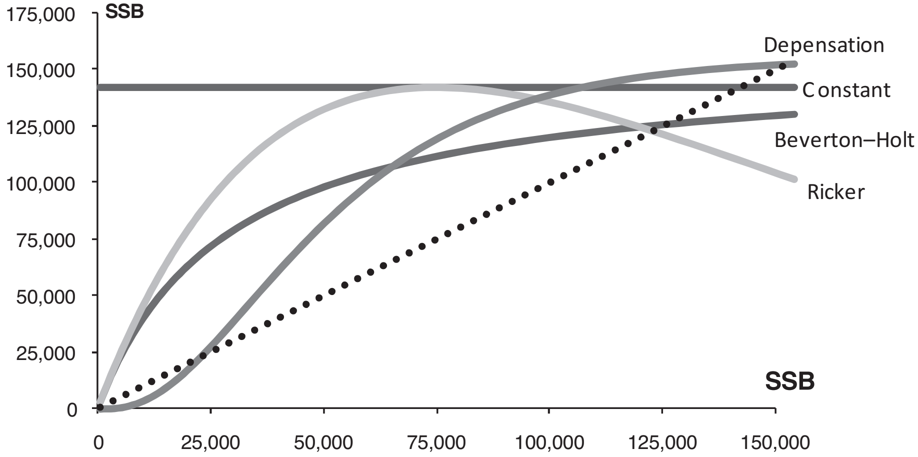


Figure 5.5 Stock generation curves.

Given this basic notion of biological equilibrium for a given level of effort, it is possible to look at several aspects of equilibria that are analogous to the Schaefer model. In order to do so, however, it will be necessary to convert vectors to scalars in order to perform the graphical analysis. As a start, we will consider the biological equilibrium of an unexploited stock by considering the stock generation curves. For a given recruitment function, this curve can be specified by plotting over a relevant range of SSB, the SSB which results from the ACP that is equivalent to FPCD[0, R(SSB)]. That is, we are interested in the SSBs (scalars) that result from the ACPs, which are equivalent to the FPCD vectors that are generated by a zero level of effort. A procedure for constructing the stock generation curve is discussed in the exercises for this chapter given in the CD.

The SSB generation curves for our recruitment functions are plotted in Figure 5.5. These curves allow for the determination of the size of the unexploited stock. The equilibrium stock size (or sizes) for a particular recruitment function will occur where the curve intersects the 45° diagonal line. That is the only place on the curve where the biomass on the horizontal axis will generate an equivalent SSB when there is no effort. Formally, the unexploited equilibrium SSB can be defined as that SSB which produces a level of recruitment that, when faced with the array of age-specific natural mortalities for a period of time equal to the number of age classes, will generate an ACP consistent with that SSB.

The unexploited equilibrium SSB in the age-class model is equivalent to the carrying capacity in the Schaefer model. From the specification equations for the elements of the FPCD, it can be seen that rather than a simple parameter, the unexploited stock size is a function of the parameters of the recruitment function and the age-specific fecundity and natural mortality rates.

Compare the equilibrium points of the various recruitment functions with the shape of the recruitment functions in Figure 5.3. Note that the Beverton–Holt and the Ricker functions generate a similar equilibrium, stock size even though

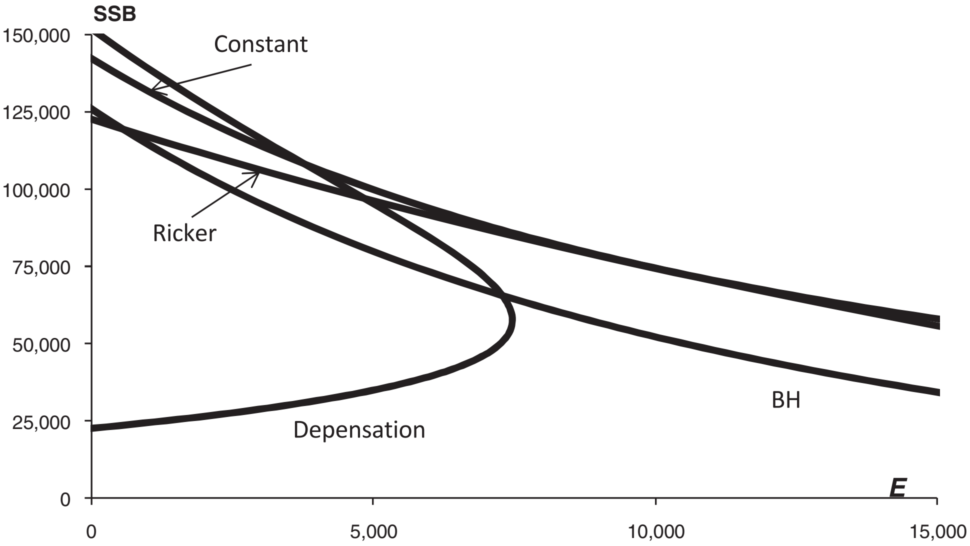


Figure 5.6 Population equilibrium curves with alternative recruitment functions.

their shapes are quite different. It must be noted that this is an artefact of the relative sizes of the other parameters in Table 5.2. Note also that the depensation recruitment function generates two possible equilibria.

It is possible to construct the equivalent of PECs using the information contained in the SSB generation curves. As a start, it is possible to construct a series of generation curves for different levels of effort and then note where they intersect the 45° line. The collection of *E* and SSB combinations will form a PEC.

However, using the FPCD for a given level of SSB, it is possible to use a search procedure to find a level of *E* that will generate the same SSB. This procedure is also explained in the exercises for this chapter. The PECs for each of the recruitment functions are pictured in Figure 5.6.

Formally, a PEC can be defined as the collection of *E* and SSB combinations where the recruitment that is produced by the given SSB will, when faced with the total mortality generated by the given level of effort and the array of age-specific natural mortality and catchability coefficients, generate an ACP consistent with the given SSB.

The PECs are similar to each other and those that follow from the Schaefer model, except that depensation PEC is concave to the vertical axis. This is because the stock generation curve for the depensation recruitment function intersects the 45° line in two places. Hence, there are two equilibrium SSBs for the relevant levels of effort. As *E* increases and the stock generation curve shifts down, the two equilibria points move closer together until they meet at the point where the curve is tangent to the 45° line. Then there is only one equilibrium point. At higher levels of effort, there are no equilibrium points.

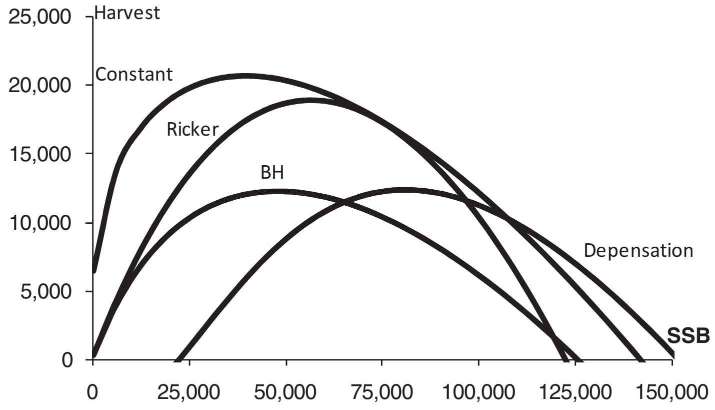


Figure 5.7 Sustainable catch with alternative recruitment functions.

The slopes of the PECs can reveal some interesting aspects of the different recruitment functions. For example, while the virgin stock size for the Ricker curve is smaller than that with constant recruitment, as *E* increases over the relevant range, the equilibrium SSBs tend to approach each other. The reason for this is that the recruitment levels for these two functions approach each other as SSB decreases.

As part of the process of generating the information to construct the PECs, it is possible to calculate total harvest for each combination of *E* and SSB. Therefore, it is also possible to prepare graphs that show the relationships between sustainable yield and SSB and sustainable yield and effort. The set of the former graphs is presented in Figure 5.7. The other set will be used below. The derivation of both will be explained in the exercises given in the CD.

These sustainable catch curves are analogous to the Schaefer growth curve in that they show what can be harvested sustainably from any stock size, but the sustainable harvest is not equal to growth per se. Recall that the Schaefer growth curve is assumed to capture the net effect of individual growth, recruitment, and natural mortality. While these items are considered in construction of the curves in Figure 5.7, the analysis is more complicated because the interrelationship between natural and fishing mortality is considered.

In the age-class model, there is no specific formula to calculate the equivalent of X_{msy} in the Schaefer model. However, the stock size that will produce the maximum sustainable yield, as well as an estimate of that yield, can be observed from the sustainable catch SSB curve. If an estimate of the SSB_{msy} is available, it is frequently used as the target stock size for management purposes. Depending on the shape of the curve, it is also possible to specify a limit stock size as a minimally acceptable stock size. See Chapter 6.

The use of SSB_{msy} as a target stock size can have very large implications (see the discussion in the next chapter). However, it is very useful to note all of the information that is necessary to come up with this estimate. In addition to the parameters of the recruitment function, and the age-class fecundity and natural mortality rates, it is also necessary to have the age-class specific catchability coefficients.

Two important points follow from this. While one would tend to think that the determination of SSB_{msy} would depend solely on biological phenomena, the catchability coefficients are from the economic and technical realm. Changes in the absolute or relative values can have significant effects on the productivity of the stock. Some may be easy to predict. For example, technologies which have higher coefficients for younger age classes will result in a decrease in sustainable yields because more fish will be taken at a smaller size.

Another point is the importance of doing the biological research correctly. The misestimates of any of the parameters could cause significant changes in the estimates of the range of safe stock sizes. We will look at this in more detail in later chapters.

5.5 Population dynamics in age-class models

Equilibrium analysis provides the framework for understanding population dynamics. However, as the second part of the name implies, it is necessary to understand why and how the stock will change if it is in a nonequilibrium state. The following two subsections briefly discuss stock change with and without fishing mortality.

5.5.1 Stock growth with no fishing

The growth of an unexploited fish stock with the Schaefer model was described using Figures 2.3 and 2.4). A comparable picture for stocks with different recruitment functions in an age-class model is shown in Figure 5.8. The parameters other than the stock recruitment functions are the same in all cases (see Table 5.2). The initial stock size and ACP is the same for all cases and was intentionally set quite low so as to clearly delineate the issues involved.

To start the analysis, note that in the constant recruitment case, all growth is completed in 20 years. After that time, the SSB remains the same. This time period corresponds to the number of age classes. It simply takes 20 years to fill in all of the age classes such that there is an equilibrium ACP where the ACP is equivalent to the zero-effort FPCD. Each age class remains the same, with natural mortality being the only thing that affects the relative size of any two adjacent age classes.

The other recruitment functions generate different paths, all of which take longer than 20 years to reach an equilibrium. Since recruitment is a function of stock size, the amount of recruitment varies as the SSB increases. Technically a true equilibrium SSB and ACP is not possible until recruitment has been the same

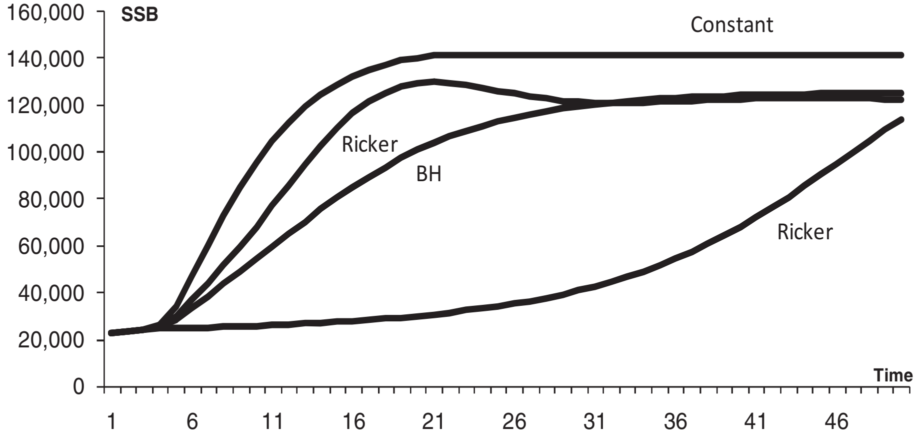


Figure 5.8 Stock growth curves with alternative recruitment functions with alternative recruitment functions.

for 20 years in a row so that the ACP will be equivalent to the zero-effort FPCD. In actuality of course, as recruitment gets to a stage where it does not change much from year to year, the curves in Figure 5.8 begin to show an approximate equilibrium. The best way to observe the intricacies of the process of achieving an equilibrium is to look at the spreadsheet used in the exercises for this chapter and notice the changes in age classes and SSB over time.

The difference in the shape of the growth paths can be partially explained by the nature of the underlying recruitment functions. With the Beverton–Holt function, recruitment asymptotically approaches a maximum as stock size grows. The SSB growth path mirrors that process. As the SSB continues to grow, annual recruitment starts to stabilize which means that as these similar-sized cohorts pass through the population, the SSB starts to stabilize.

The Ricker function produces a path where the stock reaches a maximum but then falls back down. The reduction is caused by the decrease in recruitment which results from density dependence at higher SSBs. Actually, a Ricker recruitment function may not always generate a peaked growth path. With higher natural mortality rates, the Ricker stock generation curve shown in Figure 5.5 will intersect the 45° line before the maximum is reached. Therefore, it is possible that stock growth will never put the SSB in the range where there is density dependence.

Finally, the depensation recruitment function produces the slowest growth path. Relative to the other functions, it produces the lowest levels of recruitment, and also the rate of increase in recruitment is lower, at least initially. Because of the relatively lower initial recruitment levels, the time to reach an equilibrium is longer.

The important point in all of this is that it does take time for a stock to rebuild itself even if there is no fishing. A depleted stock is not something that can be fixed overnight and the length of time it takes to rebuild depends critically on the number of age classes and the nature of the recruitment function, although the other stock parameters are important as well.

It would also be possible to derive a figure analogous to Figure 2.3, which compares stock growth with and without a constant harvest. Given that harvest is endogenous in age-class models, the comparison would have to be between with and without a constant level of effort. To be frank, however, for the most part, the lessons learned from the Schaefer analysis apply here as well. Effort does not have to be cut back to zero to get stock growth. Some growth is possible even with a positive level of effort. The levels that will generate growth will depend on the condition of the stock in terms of the size of the total biomass and the ACP and the type of recruitment. In this particular example, an effort level that would allow growth with the other three recruitment functions may not do so with the depensation function. The choice of effort level for stock rebuilding programs is a policy choice bounded by biological constraints. For now, suffice it to say to say that the stock growth curves will look similar to the one pictured in Figure 5.8, except they will reach or approach an equilibrium at a lower SSB level. The lessons that follow from the Schaefer model apply in this case as well. The equilibrium stock sizes for each recruitment function will decrease as effort is increased.

5.5.2 Stock change with fishing

Consider now the process of obtaining a biological equilibrium with a constant amount of effort. The PEC shows the equilibrium SSB for any level of effort, but it will take time to reach that stock size depending on the initial stock size. Figure 5.9 shows time paths of stock size for a constant level of effort with the different recruitment functions. The initial stock size is the virgin SSB, as determined in Figure 5.6. Of course, it is not just the SSB that matters; it is also the composition of ACP that makes up the SSB. The initial ACPs for the virgin stock size in each case are equivalent to their respective FPCD for zero effort. There is a drawdown period over which the stock moves toward the new equilibrium. Again, the stock

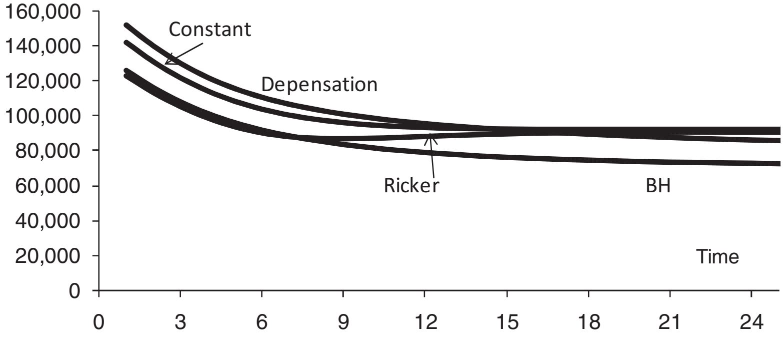


Figure 5.9 Changes toward equilibrium SSB with constant effort and alternative recruitment functions.

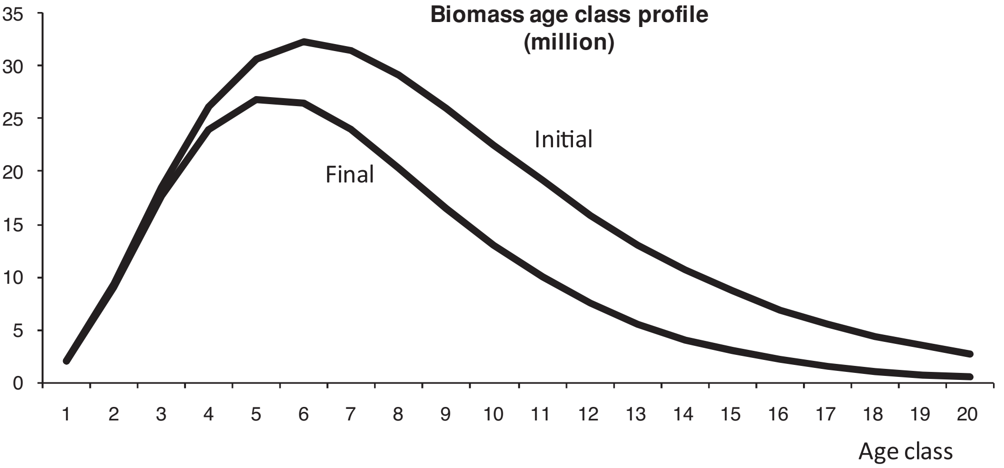


Figure 5.10 Initial and final biomass age class profile.

with the constant recruitment function reaches the equilibrium in a period equal to the number of age classes while the others take longer.

Note also that while the Ricker function has the lower initial equilibrium; it has one of the higher equilibrium SSBs with this level of effort. This is confirmed by the shape of the PECs in Figure 5.6. As *E* increases, the Ricker PEC crosses over the Beverton–Holt and the depensation curves. The reason for this is that the fishing "thins out" the density dependence for each level of recruitment because it changes the ACP where there is a smaller number in each class.

One of the important changes that occur when a stock is exploited is the composition of the ACP. Figure 5.10 shows the initial and final ACPs. Figure 5.11 shows the profile of catch in biomass. Both figures are based on the constant recruitment case, but the curves would be similar with the other recruitment functions. Note that fishing has a more significant effect on the older age classes. The number of individuals in these age classes decreases significantly, but the

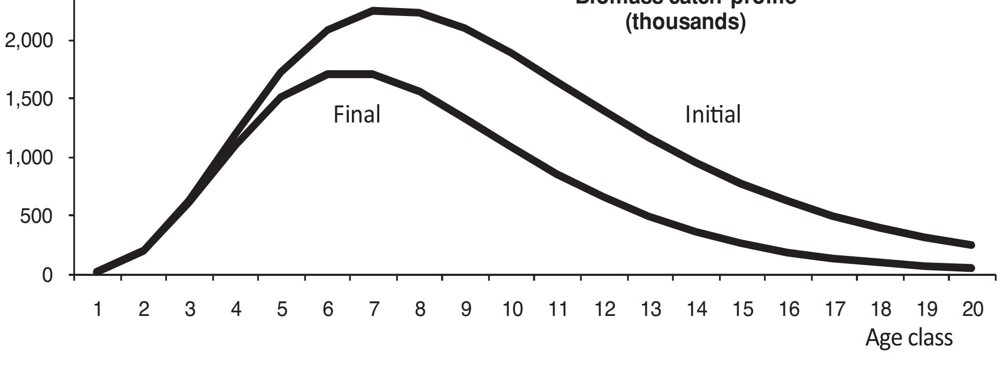


Figure 5.11 Initial and final catch age class profile.

size of the younger ages is less affected because they often have lower age-specific fishing mortalities as they have less contact with the fishing gear. This has an obvious effect on recruitment because fecundity is normally higher in older fish. It can also have an effect on the value of the catch because larger fish often have higher value per unit of biomass. In cases where there are high discards of younger fish, those age classes will fall as well, which means that older age classes are affected directly and indirectly because there will be fewer younger fish to grow old.

The concept of the change in the ACP is very important in understanding the notion of an equilibrium in a age-class model. SSB is a scalar and it is somewhat deceptive to talk about an equilibrium SSB of say, X tons, because there are actually infinite number of ACPs that would produce the same SSB. However, only one ACP is consistent with a given equilibrium SSB. It will be that profile that will remain constant, given the existing array of natural and fishing mortalities.

5.6 Bioeconomic analysis with age-class models

The biological analysis in the preceding section used Parts B, C, D, and E of the age-class bioeconomic model sketched out in Figure 5.1. We now turn to a full bioeconomic model. As shown in Figure 5.1a, this model uses a disaggregated effort analysis which tracks both fleet size and daily effort per boat. This part of the model is very similar to the one described in Chapter 3. The specific cost parameters remain the same and will not be repeated here, but they are presented in the bottom two sections of Table 3.1. As before, the parameters can be changed in the exercises to this chapter.

5.6.1 Static analysis

The static bioeconomic analysis that was developed with the Schaefer model is summarized in Figure 2.7. Using the procedures described below, it is possible to produce the equivalent curves for sustainable total revenue and total costs in terms of effort and SSB. The sustainable revenue curves in terms of effort for each of the recruitment functions are presented in Figure 5.12. The total cost curves are constructed using the average unit cost of effort. The point of intersection determines the open access level of effort. Note that given the relative size of the various parameters, the equilibrium level of effort is approximately equal for constant and Ricker recruitment and for Beverton–Holt and depensation recruitment. This, of course, does not always have to be the case. The comparative static MEY levels of effort can also be identified by inspection. The use of these curves can provide useful information to fisheries managers. It can provide rough estimates of where the fishery may end up if conditions remain the same. More to the point, it can provide general hints as to the potential economic benefits that can be achieved by controlling effort.

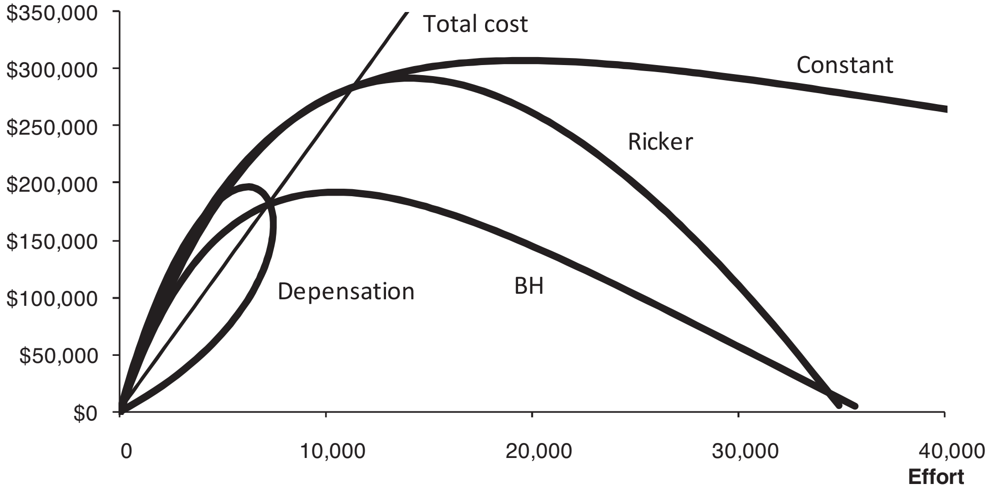


Figure 5.12 Sustainable revenue curves with alternative recruitment functions.

One interesting thing here is that the backward bending PEC for the depensation recruitment function creates the forward falling or double-valued sustainable revenue curve. The same level of effort can be associated with two different equilibrium SSBs, and hence two different levels of sustainable harvest. This has some interesting implications. For the other revenue curves, a decrease in the cost curve will lead to an increase in the equilibrium level of effort. However, with the depensation revenue curve, a decrease in cost will initially lead to an increase in effort, but eventually a point will be reached where a downward swing of the cost curve will lead to a decrease in equilibrium effort. The extreme case will be where the linear cost curve is everywhere below the revenue curve. This will theoretically lead to the extinction of the stock and an equilibrium level of effort equal to zero. The equilibrium in the forward falling portion of the revenue curve is nonstable. This will be demonstrated in more detail in the exercises for this chapter given in the CD.

It is also possible to create sustainable revenue and cost curves in terms of SSB which show the same results. However, the curve is quite messy because there is a different cost curve for each recruitment function. This is left as an exercise given in the CD.

5.6.2 Dynamic analysis

It is also possible to provide a dynamic analysis of fisheries utilization using the age-structured model. The goal is to see how the stock and the fleet size change over time. For the most part, the analysis is analogous to that in the Schafer model. However, since we are concerned about how the ACP of the stock, as opposed to some aggregate biomass measure, changes over time, there are important differences. Our discussion focuses on these differences. The time-path trajectory of SSB and *E* (in terms of both total effort and fleet size) can be generated from the simulation model developed for this chapter. While the trajectory of *E* and SSB over time is a simple way to track fishery operation, it is necessary to remember that a complete description of a fish stock requires the consideration of the ACP vector. Using SSB is a handy and policy-relevant way of collapsing the vector into a scalar. But some information is lost because there are many different ACP vectors that will generate the same SSB. This means that some aspects of the trajectories will have to be interpreted with care.

To provide a familiar frame of reference, it is possible to plot the trajectory in the context of curves that are analogous to the PEC and the EEC. They are analogous rather than identical because they can be defined only in terms of equilibrium ACPs. The derivation of the PECs has been described above and the results are shown in Figure 5.6.

The EEC is the collection of equilibrium SSB and *E* combinations where total revenue is equal to total costs. While it is not possible to solve for this function analytically, it is possible to derive it numerically. Using a procedure described in the exercises to this chapter, it is possible to specify a range of SSB and then find the corresponding levels of *E* where the above condition holds. Because it is necessary to use aggregate *E* in these numerical protocols, it is necessary to use the average unit cost of effort in the calculations. Formally, the EEC can be defined as: The collection of *E* and SSB combinations where the recruitment produced by the given SSB, when faced with the total mortality generated by the given level of effort and the array of age-specific natural mortality and catchability coefficients, will generate an ACP that will produce a total revenue equal to the cost of that effort.

Figures 5.13–5.16 present the PECs and EECs for each of the recruitment functions. For completeness, each case is shown in terms of total effort and fleet size. In recalculating the PEC and the EEC from effort to fleet size, it is assumed that each vessel produces the profit-maximizing level of effort for the given stock size.

The trajectory for a developing fishery is shown in Figure 5.13, but other combinations of intial SSB and *E* are used in the other figures for the purposes of comparison. Many more examples are provided in the exercises given in the

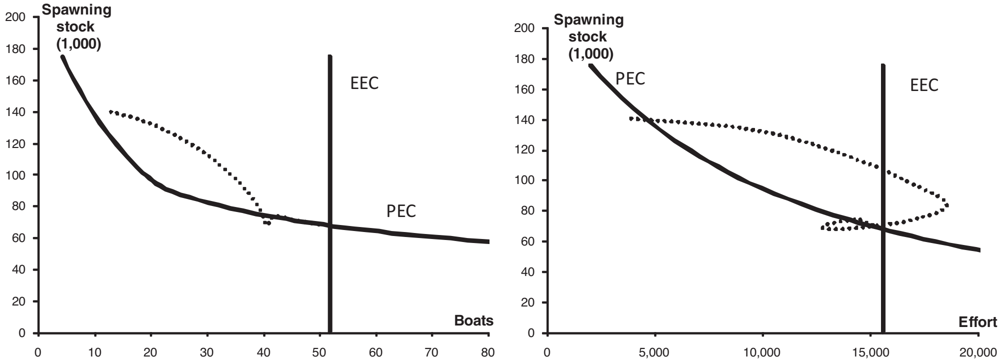


Figure 5.13 Constant recruitment.

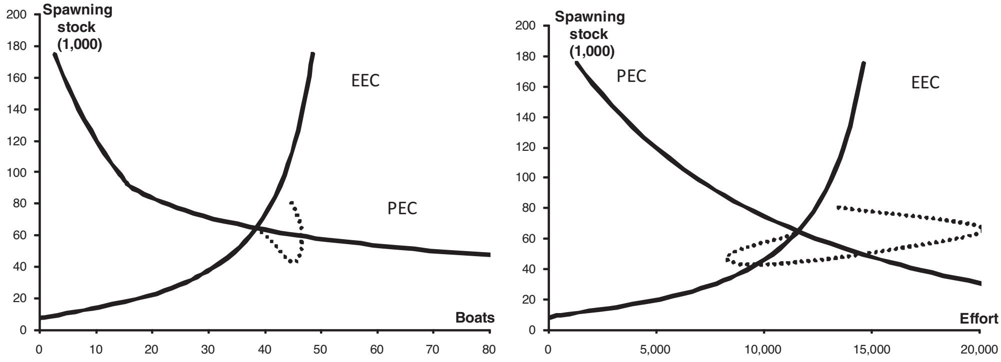


Figure 5.14 Beverton–Holt recruitment.

CD. Along the trajectory, the SSB is not necessarily at an equilibrium, and the vessels will not be operating at the minimum of the average cost curve.

The PECs have been discussed above, and it will be worthwhile to make a few comments about the shape of the EECs. Recall that the EEC is a horizontal line in the simple Schaefer model because of the assumption of a linear production function. Profit per unit of effort is a function of stock size only, and there is only one stock size where net returns equal zero.

Things are more complicated in the age-class model. The EEC for constant recruitment is a vertical line. Recruitment does not vary with stock size, and there is only one level of effort where total revenue for that constant recruitment will equal total cost. With the other recruitment functions, the relationship between SSB and the level of *E* where net revenues equal zero will depend on the relationship between SSB and recruitment. The EEC for the Beverton–Holt and the depensation functions will have a positive slope throughout. As SSB goes up, there is an increase in recruitment and the stock can stand more and more pressure before net revenues are pushed to zero. However, the Ricker recruitment function will have a backward bending part when recruitment decreases with effort.

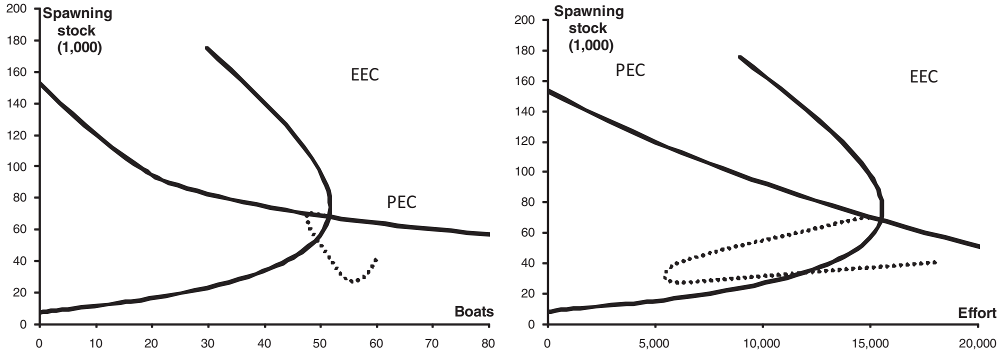


Figure 5.15 Ricker recruitment.

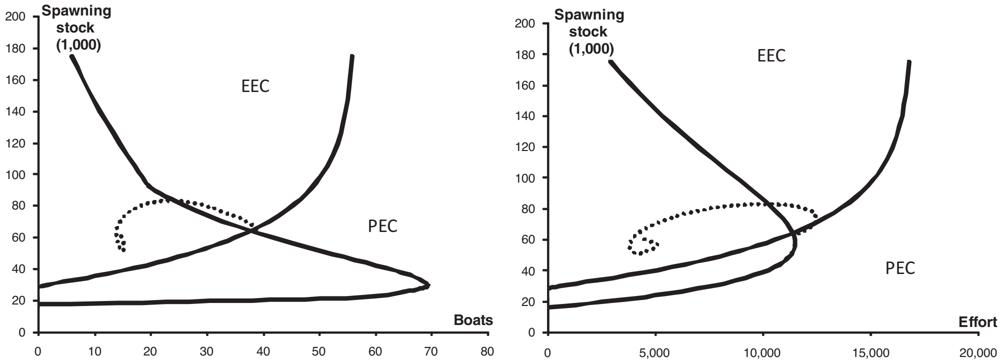


Figure 5.16 Depensation recruitment.

Returning to the trajectory analysis, except for certain changes due to the richness of the age-class model, the general results are similar to the lessons learned from the same analysis in terms of the Schafer model. To repeat, the chief goal of this chapter is to describe the age-class model so as to provide a better understanding of the population dynamics underlying fisheries management and a richer and more rigorous way to study real-world management problems.

These models will be used in the regulation discussion below, but there are some points that are worth noting at this point, however. First, the points on the PECs and the EECs represent not only a combination of SSB and *E*, but also a specific ACP vector (see the definitions above). This means that at their intersection, the related ACP is the same for both curves. In contrast, at points on the trajectory, there can be a variety of ACPs associated with any SSB, depending on the initial ACPs and the age-class natural and fishing mortalities. However, if the trajectory reaches and remains at the intersection of the PEC and the EEC, there will not only be an equilibrium SSB, but it will have an equilibrium age-class distribution as well.

Because there can be many possible ACPs for each SSB point, the PEC and the EEC do not reveal as much information about the potential path of the trajectory. Recall from the analysis of Figure 3.1 above that in the Schaefer model, there is a specific direction of change in the trajectory in each of the four quadrants formed by the EEC and the PEC. Once the trajectory crosses one of the curves, the general direction of change of the trajectory will be altered. It can be seen that this is not the case with the age-class model, however. In all of the cases, the trajectory in terms of aggregate effort continues to show a decrease in SSB but an increase in effort after the trajectory crosses the EEC. The EEC is defined for a certain SSB and a certain ACP that will generate zero net revenues for the given level of *E*. The fact that effort keeps increasing in this case is that although SSB has decreased, the ACP that actually exists is such that the net revenue is still positive.

As a final point, note that the backward bending PEC for the depensation recruitment function generates the same phenomena that followed from the forward falling sustainable revenue curves. Lower costs will shift the EEC down. Therefore, at first, lower cost will increase equilibrium effort, but eventually decreases in cost will cause it to fall. If the EEC falls below the PEC, the equilibrium level of effort will fall to zero.

In summary, while the EEC and the PEC do intersect at the bioeconomic equilibrium, because of the assumptions that must hold to construct them, they only provide general hints about the vectors of motion in the various parts of the graphs.

The trajectory is based on the actual situation with respect to the makeup of the ACP or the way the aggregate amount of effort is spread over the operating fleet at any point in time. While the analysis of the sustainable revenue and cost curves can provide summary and long-term projections about fishery operation, the trajectory can predict detailed changes in SSB and fleet conditions. Of course, the reliability of the predictions will depend on the accuracy of the estimation of the values of the various parameters.

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Suggested Reading

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Chapter 6

The fisheries management process

6.1 Introduction

The job of controlling fisheries can be divided into two tasks. The first is the selection of what is the desirable amount of harvest to be taken, given the current biological and economic circumstances. The second is to implement regulations such that actual harvest corresponds to the desired harvest taking into account management agency and participant costs as well as the short- and long-term effects of how the regulations will affect participant behavior. The two are not completely mutually exclusive and it will be necessary to consider the interrelationships as we proceed further. For purposes here, we call the first task fisheries management and the second task fisheries regulation. We discuss fisheries management in this chapter and fisheries regulation in the next.

6.2 The paradigm of modern fisheries management

In our discussion of dynamic optimal utilization, we discussed the twin issues of what stock size to target and what path to use to get from the current stock to the target stock. While those questions followed from a narrowly defined model designed to maximize the present value of net revenues, these same issues are central to the paradigm that is at the core of modern-day fisheries management policy (see Suggested Readings). The development of this paradigm has been an evolutionary process and much of it is based on the Precautionary Approach to Fisheries Management, as developed by the Food and Agriculture Organization of the United Nations (see FAO, 1996). We will start our discussion of the paradigm by summarizing the basics. We will then go back to discuss the process that led to its development and to fill in some of the details.

Stripped to the core, the basic concept is that the goal of fisheries management is to achieve, on a sustainable basis, a target stock size. What that stock size should be is a policy decision taking into account political and social management objectives and constrained by the current stock, fleet, and environmental conditions. It is not a scientific determination per se. The target stock size should be the one that will allow for the maximization of sustainable "benefits" from the use of the fish stock. In addition to the amount of benefits, the ability of the stock to maintain itself when subject to environmental shocks may also be something that should be considered. And all else equal, the higher the stock size, the more resilient the stock will be. There may be a trade-off between increasing resiliency and accepting lower sustainable benefits.

But how should these benefits be defined? Conceptually, it should be possible to plot relationships that show how different important variables, such as employment and balance of payments, vary with stock size. This would give a broader perspective for choice than merely noting where yield and net economic returns are maximized. Further, it may be possible to place relative weights on each of these variables such that the curves could be summed to show at what stock size the weighted sum of benefits is maximized.

But, quite frankly, the majority of fishery management programs around the world specify that the proper goal is to maximize long-term sustainable harvest. That is, the target stock size should be X_{MSY}, the stock which will produce the maximum sustainable yield. This is effectively what is required by the Magnuson Stevens Act in the United States (see Magnuson-Stevens Act Provisions, 2009). It should not be necessary to repeat that most likely X_{MSY} is not the stock size that will allow for the maximization of net returns either in sustainable or present value terms (see Chapter 4). Further, neither dynamic maximum economic yield (DMEY) nor maximum economic yield (MEY) can be specified solely in terms of a given stock size. It is also necessary to maximize the returns from harvesting the sustainable harvest from that stock size.

In a notable development indicating that the lessons of bioeconomic analysis may be filtering into real-world policy, Australia has recently issued a policy statement that specifies X_{MEY} as the required target stock size. It is clear that they are referring to what we have called static MEY because the goal is to maximize sustainable net returns. It also specifies that X_{MEY} is greater than X_{MSY}, which is consistent with recent research which shows that this is the correct relationship even when considering DMEY (see Grafton et al., 2007). The Australian policy also includes the requirement to maximize net returns at the target stock size.

Once the target stock is specified, the general procedure is to use a target/limit approach to set an ongoing policy designed to achieve or maintain the target stock size, given the stochasticity of the marine environment, the real-world constraints on the accuracy and availability of data, and the existing political institutional structure for making decisions. We return to these three issues below. The basic components of the paradigm are a *predetermined* target stock size, a *predetermined* limit stock size, and *predetermined* harvest control rules to keep the stock at or moving toward the target size, with provisions for extra urgency and stringency when the stock is near or below the limit stock size.

A harvest control rule is an algorithm that, at any point in time, sets the desired harvest limit as a function of stock size. The application of the harvest control rule also uses a target/limit framework. The harvest control rule generates a limit harvest level that is meant to be the largest amount that can be taken and still allow the target stock to be maintained or achieved in a reasonable period of time. When making recommendations for the actual allowable harvest, the target harvest level is set below the limit harvest level as a precaution to keep the stock on the desired growth trajectory in case the estimates of current stock size, predicted stock change, or the limit harvest level are incorrect.

This management paradigm considers both stock and flow aspects of management using target and limit reference points. The target and limit stock sizes provide a basis for judging the current state of the stock. If the current stock is below the limit stock size, the stock can be considered *overfished*. If the current harvest rate is above the limit harvest rate, *overfishing* of the stock is occurring in the sense that the stock is not on the desired trajectory toward the target stock size.

The practical application of the paradigm for modern-day fisheries management requires the data collection and research capacity to perform stock assessments that can provide current estimates of stock size and predictions of how different harvest levels will affect near-term stock growth.

6.3 Historical perspective on the development of the paradigm

The component parts of this paradigm can be better understood by explaining the context in which it was developed. For the most part, it was designed to address the almost universal perception that the existing fisheries management and regulation programs were failures. Among others, two distinct reasons for the failure were singled out. The first was data limitations and the second was the politicization of management.

The problem of limited data is pervasive and multidimensional. For one thing, there is a lack of adequate biological information concerning stock status and the expected effects of fishing. In short, it is not always possible to develop biological models of actual fisheries using either the Schaefer surplus production model or full-fledged age-class models. In some cases, there is no information, and in most others, it is incomplete. And even when there is information, there are many types of uncertainty.

While a more detailed analysis of risk and uncertainty in fisheries management and regulation is presented in Chapter 12, a brief description in the context of this discussion will be useful here. Many types of uncertainty have been identified (see Francis and Shotten, 1997). For example, while recruitment may be related to the size of the spawning stock biomass, there is considerable variability involved. There are limits on how well these types of things can be predicted. This is called *process uncertainty*.

There are three related, but conceptually distinct, types of uncertainty involved with empirical biological research on stock population dynamics.

Measurement and sampling error in data collection is called *observation uncertainty*. Model uncertainty involves the choice of the correct functional form for a particular relationship. Does the equation actually mimic the natural process? Is recruitment best captured by a Beverton–Holt or a Ricker equation? Finally, there is uncertainty related to the process of estimating the parameters of whatever equation is chosen. These two types of uncertainties are often collectively referred to as *scientific uncertainly*. See below.

There are also uncertainties in the management process itself. Setting an allowable harvest is one thing, but making sure that the actual harvest is constrained to that amount is another. This is called *implementation uncertainty*, and it depends on how well the activities of participants can be monitored and controlled.

The second motivating factor in the development of this paradigm was the perceived inherent weaknesses in the institutional structure of fisheries decision making. Problems often arose with respect to making appropriate decisions on safe allowable harvest levels in cases where there was a tradeoff between stock maintenance and employment in the fishing industry (see Walters and Martell, 2004, Chapter 2). Politicians are often myopic when making conservation choices because the benefits are long-term and uncertain while the costs are immediate and certain. That is, they know for sure that a decision to cut harvest will have immediate and certain effects on employment for easily identified groups which are part of their constituency. However, the benefits are viewed as being in the nebulous form of stock improvement, are of uncertain size, and will have uncertain effects on industry participants. In addition, they will not occur for several years and it is hard to identify the specific beneficiaries. This frequently resulted in allowable harvests that were higher than may have been prudent.

Another aspect of political decision making is that the hard decisions are mostly made in times of crisis. Almost by definition, management questions only have a high political profile when stocks are in trouble because that is when serious harvest reductions are proposed. However, when stocks are in trouble, participants already have their backs to the wall. They are often in serious financial straits and, because of the lack of other employment alternatives, are not in a position to suffer harvest cuts and wait for the stock to improve. The fact that many important conservation decisions are not made until the situation is already precarious makes it even less likely that political decisions will support necessary conservation.

The harvest control rules and the concept of the limit stock size were designed, in part, to address the problems created by the institutional structure for decision making. It may appear that harvest control rules reduce managerial input because the allowable harvest is determined by applying a simple rule. But that is not the case. The policy choice is just put back one level. There are actually an infinite number of control rules that, if followed, will lead to the target stock size. Their shape and position will depend on the time allowed to get to the target stock size, and whether the greater burden of reduced harvests will occur early or late along the harvest path. These are clearly issues for policy choice, but the important thing is that these choices are made *a priori*. The control rules are to be developed in advance taking a long-run view of things, so that the hard decisions will not have to be made during times when there is a stock crisis. Further, the primary emphasis is on achieving or maintaining the predetermined target stock size. Proper use of the control rule will prevent extraneous issues from being introduced by the political process during the setting of annual allowable harvest.

The predetermined limit stock size also helps to reduce political problems. The situations in which special management steps need to be taken are set in advance. There is no room for political debate about how bad things really are and what needs to be done. The decisions have already been made.

Conceptually, setting a limit stock size is fairly straightforward. On the one hand, it is the stock size below which there is serious concern about the stock's ability to recover to the target stock size. Or, look at it from a slightly different point of view, given the stochasticity of the natural system, a management regime where the stock size fluctuates around the target size, within reasonable bounds, should be considered a success. This is especially true if the control rule has been properly set and is properly implemented. However, there must be some limit as to what constitutes acceptable fluctuations below, or long-term deviations from, the target stock size. The limit stock size can be thought of as the lowest stock size that can be considered as being within the acceptable bounds.

6.4 The specification of harvest control rules

In addition to specifying a predetermined method of selecting annual harvest rates, harvest control rules were also developed to help address stochasticity, data limitation, and uncertainty issues. This and other aspects of the paradigm can be explained in the context of the sustainable catch curve that was introduced in Chapter 5. Figure 6.1 contains the sustainable catch curve for the Beverton–Holt recruitment function illustrated in Figure 5.7. The other curves will be explained below.

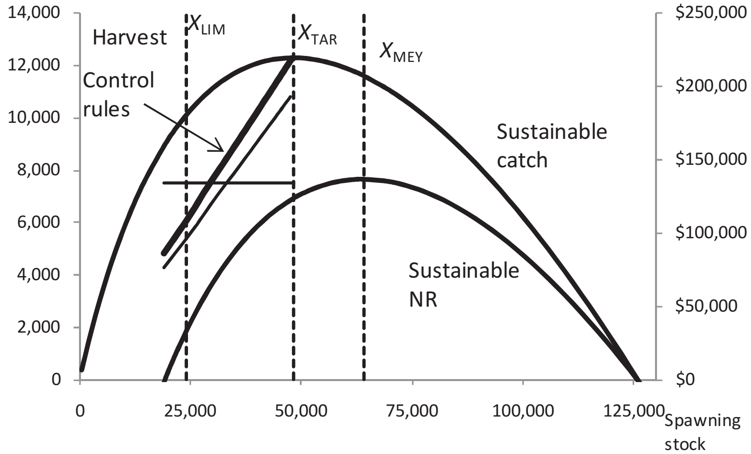


Figure 6.1 Sustainable catch and control rule curves.

The process for deriving the sustainable catch curve is explained above, but it will be useful to recall that the necessary inputs to derive it include the stock recruitment function, and the age-class coefficients for fecundity, individual weight, natural mortality, and catchability. While the data requirements may be daunting, the results can be very useful for many things, not the least of which is selecting a target (spawning) stock size. Then, given an estimate of the current stock size, as was demonstrated in Chapter 5, it is also possible to project how the stock size will change for a specified level of harvest.

But let us take a minute and interpret this curve and its ramifications in view of the discussion about uncertainty and stochasticity. The whole point is that it is difficult to know the accuracy of the point estimates of the coefficients used in constructing the curve. A different set of coefficients, even if the differences are quite small, can lead to some significant changes in the shape of the curve. A manager working to devise a management program may be tempted to look at the sustainable catch curve and infer that it provides a picture of the characteristics of the stock. But it would be much more realistic to conclude that it provides "best" or, at least, current estimate of the characteristics of the stock. In another year, the current data may show something quite different. For example, the estimate of X_{MSY} could change.

Bearing this in mind, let us see how this deterministic representation of stock characteristics can be of use in choosing annual allowable harvests. As a frame of reference, target and limit stock sizes have been included in the figure. The target has been set at X_{MSY}, and following a frequently used rule of thumb, the limit stock size has been set to one-half of X_{MSY}. The specification of a spawning stock limit reference point, however, should consider the resilience capacity of the species and its corresponding longevity. The graph of sustainable net returns as a function of stock size is also included in the figure. In this regard, following the Australian policy, the target stock size would be X_{MEY}.

The sustainable catch curve is a useful frame of reference because it provides a relative indicator as to whether a particular level of harvest will cause the stock to increase or decrease. At any stock size, a harvest level below the curve will cause the stock to grow and vice versa. Therefore, if the stock size is less than X_{TAR}, catch must be less than the sustainable catch in order to have the stock growing toward X_{TAR}. The greater the difference between the sustainable harvest and the planned harvest, the faster will be the expected stock growth. We return to the interpretation of the curves in view of the data uncertainties below.

Let us now turn the discussion to the design of harvest control rules. Harvest control rules specify the allowable level of harvest according to the current stock size. In some cases, there are two distinct control rules. The normal control rule applies in cases where the current stock size is above X_{LIM}, and the notion is to keep that stock moving toward the target stock size at a reasonable rate. The stock rebuilding harvest control rule comes into effect if the current stock size ever falls below X_{LIM}. While in reality there is no razor's edge cut off, the limit stock size marks a boundary where a different and stricter control rule should be followed. When the stock is below the limit, it is implicitly assumed that the normal control rule is not effective, because of stock characteristics, biological or environmental variability, or the inability to enforce regulations. The stock rebuilding harvest control rules are specified to achieve the target stock size within a specified time period, often equal to the number of year classes in the stock.

The dark heavy line intersecting the sustainable catch curve at X_{MSY} in Figure 6.1 is an example of a commonly used normal harvest control rule. It is derived by applying the fishing mortality rate that will produce MSY, F_{MSY}, rate to the current stock size. Recall that the same fishing mortality rate will provide a different catch level when applied to a different stock size. The difference between the normal harvest control rule and the sustainable catch curve is larger at smaller stock sizes. The control rule gets a little more conservative if stock size falls. When stock size equals X_{MSY}, the allowable harvest will equal the MSY.

The other two control rule curves in Figure 6.1 represent possible rebuilding control rules if the current stock falls below X_{LIM}. Both are constructed assuming the current stock size at the time at which the rebuilding plan is initiated is the open access equilibrium stock size, which can be identified as the lower point where the sustainable net revenue curve intersects the horizontal axis. They both have lower allowable harvest for each stock size than does the normal harvest control rule because the required increase in stock size is because of due to the specified time to achieve the target.

The horizontal control rule curve is a constant *harvest* rule and the other is constant *fishing mortality* rule curve. Both of the rules will cause the stock to grow from the limit stock size to the target stock size in 20 years. When the target stock is reached, harvest can increase to the MSY level. The constant harvest rule is oftentimes favored by industry. For one thing, it allows for higher harvest in the early part of stock rebuilding program. The payback comes at the other end of the curve. Also, the constant harvest is sometimes better for both industrial and fisheries management planning.

Figure 6.2 shows the deterministic stock growth trajectories of the different harvest control rules assuming the same initial stock size. The F_{MSY} control rule

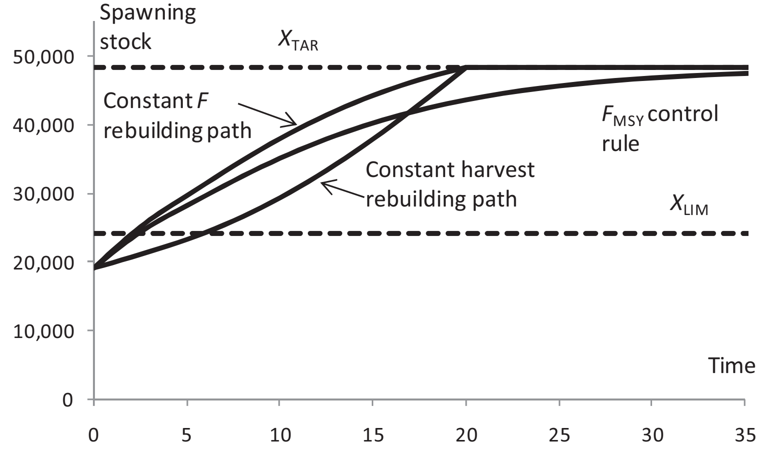


Figure 6.2 Stock growth trajectories for different control rules.

takes quite awhile to get to the target stock size but it does keep the stock in that neighborhood. By design, both of the stock rebuilding control rules reach the target stock at the same time but the constant F control rule produces more growth in the early years of the rebuilding plan.

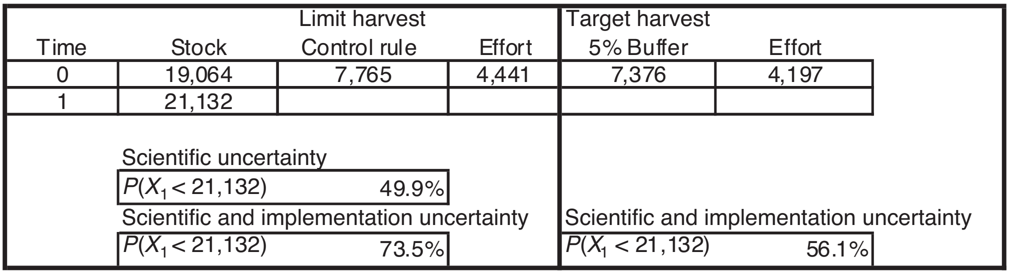
Figure 6.1 can be used to provide a geometric interpretation of the operation of this management process. Each point in the graph represents a combination of harvest and stock size. Any point between the limit and target stock size and below the operative control rule represents a case where management issues are being addressed. The stock is not overfished; it is either at the target size or is in the process of growing toward it at an acceptable rate. In this range of stock sizes, points above the control rule represent combinations of stock size and harvest levels where overfishing is occurring, in the sense that stock is not on an acceptable growth trajectory to achieve the target size. The stock size is okay but the conditions are such that trouble may be looming. At points between the control rule curve and the sustainable harvest curve, the stock will be growing, but not fast enough. Points above the sustainable harvest curve represent situations where stock size will fall.

On the other hand, points to the left of the limit stock size represent situations where, by definition, the stock is overfished. Overfishing is a flow condition, having to do with whether the stock is moving in the right direction and at the right speed, but overfished is a stock condition. If the stock falls below the limit stock size, a more stringent harvest control rule must be implemented. Points below the limit stock size and below the rebuilding plan control rules represent situations where the stock is overfished but overfishing is not taking place. Things are not good but the problem is being addressed. Points above the rebuilding harvest control rule line represent stocks that are both overfished and where overfishing is taking place. Things are bad and may be getting worse.

6.5 Limit and target harvests

In Figure 6.1, the operative harvest control rule defines the limit reference point for harvest. A limit reference point can be thought of as a condition which is considered to be undesirable and which management action should attempt to avoid. Viewed in this manner, the limit control rule is a demarcation line marking the distinction between safe fishing and overfishing. The limit and target framework is applicable to harvest as well as stock size. The harvest set by the control rule is viewed as a limit that is not to be surpassed. It makes sense to set a target harvest level that is below the limit to ensure that actual harvest does not surpass the limit.

There are at least two justifications for inserting a “safety cushion” between the limit and the target catch levels. The first is biological uncertainty. The control rule is specified to set a harvest level that will allow for the necessary stock growth. But given the uncertainty surrounding the specification of the sustainable catch curve and the stock projection model, setting a target harvest below the



		Limit harvest		Target harvest	
Time	Stock	Control rule	Effort	5% Buffer	Effort
0	19,064	7,765	4,441	7,376	4,197
1	21,132				

Scientific uncertainty

$P(X_1 < 21{,}132)$	49.9%

Scientific and implementation uncertainty

$P(X_1 < 21{,}132)$	73.5%

Scientific and implementation uncertainty

$P(X_1 < 21{,}132)$	56.1%

Figure 6.3 Application of control rules.

limit harvest specified by the control rule can help to address the uncertainty and increase the probability that the desired growth will indeed take place.

The second justification is to address implementation uncertainty. Actual harvest in a fishery is often greater than the allowable harvest due to difficulties with monitoring and enforcement. Setting a lower target will help to ensure that the actual harvest will be less than the limit even with the slippages caused by imperfect implementation.

But how can the target/limit concept be applied in a meaningful way? The limit harvest level is set by a predetermined control rule. Can an analogous procedure be specified for setting a target harvest level? Or to put it another way, how big does the buffer between the target harvest and limit harvest have to be to ensure that uncertainty is properly considered?

Let us consider this in more detail using the simulation program for the age class model given in Chapter 5 as a stock projection model. Figure 6.3 summarizes the first year results of applying the constant harvest stock rebuilding control rule shown in Figure 6.1. In period 0, the stock is assumed to be 19,064. With a harvest level of 7,765, using the point estimates of the parameter values, the deterministic estimate of projected stock size in the next period, X_1, is 21,132. The purpose of the harvest control rule is to keep the stock growing on a specified trajectory. The deterministic stock projection model shows that the specified limit harvest will generate a specific stock size which can be called the interim target stock size. But given the admitted uncertainty about the point estimates, it is reasonable to ask what are the chances that the actual stock in the next period will equal the interim target stock size.

This is equivalent to asking what the projected stock size would be with different point estimates for the parameters. One way to look at this is to perform a Monte Carlo analysis. Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling to compute the results. With respect to our problem, the procedure is to first specify the inputs to consider. For purposes of this example, variability in age-class natural mortality and catchability coefficients as well as the size of the age classes in the initial period are considered. The next step is to generate random values for these inputs and perform the deterministic computation of X_1 using these values. In the example, for each input the random value was generated by multiplying the parameter by a random number drawn from a normal distribution with a mean of 1.0

and a standard deviation of 0.05. After repeating the process many times, the probability distribution of X_1 is calculated.

6.6 Monte Carlo results with scientific uncertainty

Although it is technically a complex process, there are several commercial products that make it quite easy to perform the necessary steps. The program used here is Crystal Ball. The details are left to the exercises Chapter 12 in the CD. The results of the repeated experiment are presented in Figure 6.4. The distribution of the projected level of X_1 is very much like a normal distribution around our deterministic result. In this particular case, the probability that X_1 will be less than or equal to interim target stock size is 49.9%. If the probability distributions correctly capture the range of values that could be the "correct" estimates of the parameters, this means that about 50% of the time the actual value of X_1 will be above the deterministic estimate and 50% of the time it will be below it.

While this conclusion is directly related to the probability distributions selected for the Monte Carlo analysis, it may have some general application. If the errors in the estimation of the various parameters in the real world are likely to be normally distributed, this general conclusion will hold. Put another way, unless there is reason to believe that the estimation procedures will likely be biased one way or the other, these are the sort of results that can be expected from performing a Monte Carlo analysis with respect to scientific uncertainty.

Perhaps a more interesting issue is the range of the predicted value of X_1. It may not be very comforting for managers to learn that if they apply the harvest limit suggested by the deterministic model, the stock will grow at least by the predicted amount only 50% of the time. But given the uncertainty involved, that is way the process works. The dispersion around that deterministic estimate can be more informative. In this case, it is only about ±5%.

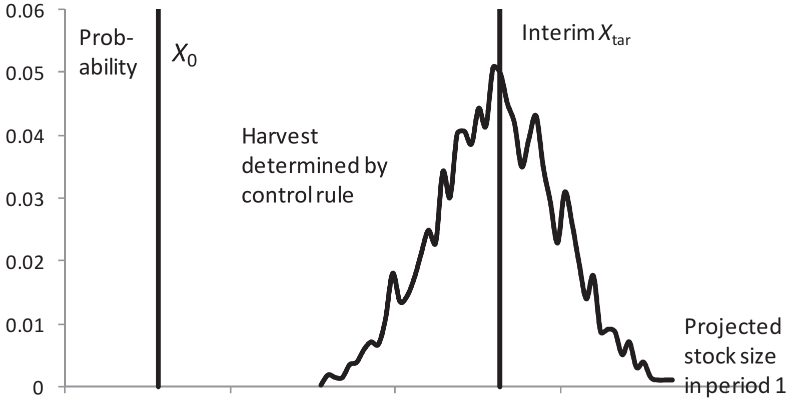


Figure 6.4 Probability distribution of projected stock size.

6.7 Monte Carlo results with scientific and implementation uncertainty

While the probability distribution in Figure 6.4 provides some information on the expected effects of a particular harvest level on stock size, it only tells part of the story because it only considers scientific uncertainty. The Monte Carlo analysis was specified to let the level of the biological parameters vary in the different replications. But the amount of effort necessary to take the limit harvest was not varied. The question under consideration was what is the likely range of X_1, given the existing stock size and a specified harvest level when the biological parameters are allowed to vary.

A more complete picture is possible if implementation uncertainty is simultaneously considered along with scientific uncertainty. Implementation uncertainty deals with the ability to actually keep harvest to the allotted amount. Note from Figure 6.3 that the required amount of effort to produce the limit harvest level is 4,441. The possibility of imperfect implementation can be considered by performing another Monte Carlo analysis that allows the biological parameters and the level of effort to vary. For our purposes, the amount of effort used in each of the replications was obtained by multiplying the deterministic amount of effort by a number drawn at random from a minimum extreme distribution where the likeliest value is 1.1 and the scale is 0.05. Numbers less than 1 will be generated about 18% of the time. This was meant to capture the fact that it is often the case that monitoring and regulation programs allow actual effort to be higher than that which is necessary to take the desired harvest.

The distribution of X_1, when both scientific and implementation uncertainty are considered, is shown as the solid curve in Figure 6.5. It covers a lower range of values than does the distribution which only considers scientific uncertainty. The expected stock size will be below the interim target stock 73.5% of the time. Obviously, the numbers in this case study are hypothetical, but the analysis

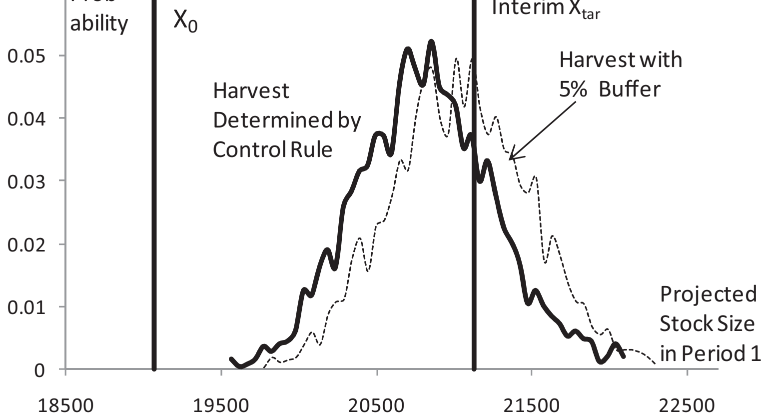


Figure 6.5 Comparison of range of projected stock sizes with and without buffers.

demonstrates the way in which different types of uncertainty can be addressed. Given the accuracy of the parameter estimates and the observed ability to enforce harvest limits, information on the distribution of the expected stock size relative to the interim target stock size provides some indication of the need for, and the likely size of, buffers between limit harvest and target harvest.

Going one step further, it is possible to show how the distribution will change when a target harvest level less than the limit harvest level is used as the basis for management. For example, setting a target harvest level equal to 7,376, which is 95% of the limit harvest, would require that effort be reduced to 4,197. Running the Monte Carlo analysis again using that level of effort generates the dotted distribution function in Figure 6.5. Note that everything is shifted to the right. The probability that X_1 will be below the interim target stock decreases to 56.1%.

This can be formalized by considering the buffer between the limit harvest and the target harvest as a policy variable. In this case, we would be interested in how the probability of being below the interim target stock size will change as the buffer (B) is increased. Letting X_{IT} represent the interim target stock size, we can represent this probability as:

$$P(B) = P(X_1 < X_{\mathrm{IT}} \,|\, B) \tag{6.1}$$

We have already determined this for B equal to 0 and 5% of the limit harvest. Figure 6.6 shows the full range of this function where the buffer is expressed as a proportion of the limit harvest level. In this particular example, the probability of the projected stock being less than the interim target stock size falls to 0 when the buffer approaches 30% of the limit harvest level. Note that the curve appears to be convex, at least in the lower range, which means that there are diminishing returns from increasing the buffer.

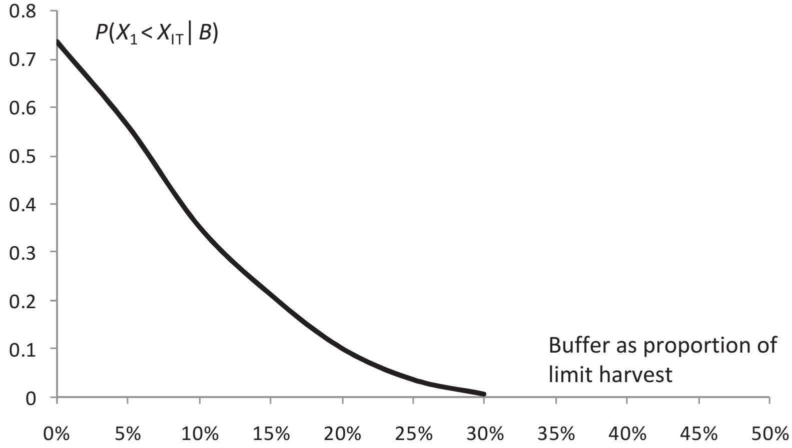


Figure 6.6 The relationship between the probability of being below the interim target stock size and the size of the buffer.

But how can this information be used in a meaningful way? One possible rule of thumb would be to specify a maximum acceptable probability of not achieving the interim target stock size. For example, it could be set equal to the value that results when only scientific uncertainty is considered. In our case, this was about 50%. So if we want to insert a buffer to counteract implementation uncertainty, a buffer of approximately 6.4% of the limit harvest would suffice.

But it is also possible to look at this in terms of a simple risk analysis. There is a cost to setting a buffer. At minimum, it is the loss of the net value of the output of fish forgone. That is, the difference between what consumers are willing to pay for that output and what it costs to harvest, process, and distribute it.

Conceptually, there is also a loss (L) for missing the interim target stock size. This is a very hard thing to estimate because of the illusive chain between missed targets in a single year and forgone future benefits. A possible goal would be to minimize the expected costs of implementing buffers.

Letting $P(B)$ represent a shorthand notation for $P(X_1 < X_{\mathrm{IT}} \mid B)$, the function for the cost that is to be minimized can be written as:

$$C = P(B)L + (B/\mathrm{LH})\mathrm{NV} \tag{6.2}$$

where B is the buffer and LH is the limit harvest level that follows from the control rule. The term NV represents the net value of producing the limit harvest level. As B is increased from 0 to LH, the cost of the buffer increases from 0 to 100% of NV. The first-order condition for a minimum is:

$$-P'(B)L = \mathrm{NV}/\mathrm{LH} \tag{6.3}$$

Since $P(B)$ is an inverse function of B, $-P'(B)$ is positive. The simple economic interpretation of this is that the optimal level of B occurs where the marginal reduction in the value of expected losses is equal to the marginal cost of increasing the buffer, which is the net value per unit of harvest.

Note that reformulating the first-order condition obtains the following:

$$L = \frac{\mathrm{NV}}{\mathrm{LH} \times [-P'(B)]} \tag{6.4}$$

This allows for the calculation of the minimum value of L necessary to justify a given buffer. This value of L is the inverse of the negative of the slope of the $P(B)$ function at the particular buffer level times the per unit value of harvest. The discrete values of the slope of the probability curve are plotted in Figure 6.7. In our example, it takes a while before diminishing returns set in.

Since it is possible to obtain estimates of NV and $P'(B)$, it is possible to state some bounds for the size of L that are necessary to justify a particular buffer. For example, if NV/LH is \$5,000, the expected loss will have to be 10 times as large, or \$50,000, to justify a buffer of 20%. The factor of 10 comes from taking the inverse of the value of $P'(B)$ when the buffer is 20%.

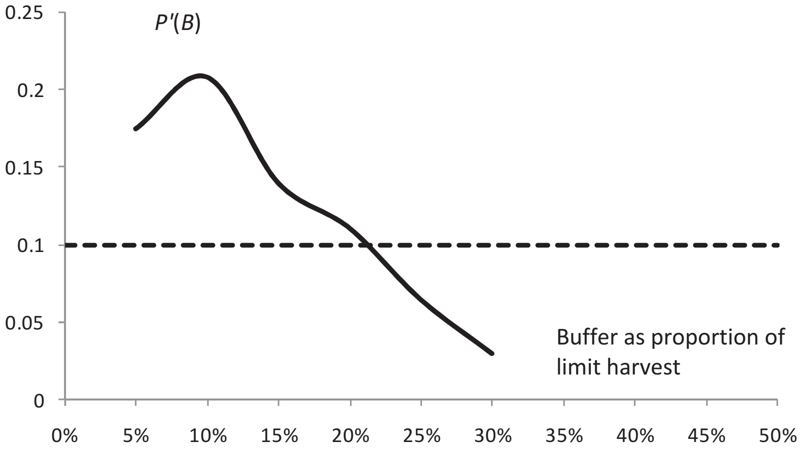


Figure 6.7 Using the value of $P'(B)$, it is possible to estimate the minimum value of L necessary to justify a given buffer.

It can be seen that the problem of determining the appropriate level of allowable harvest is very complex and it will require a delicate balancing of science and policy. But setting the allowable harvest level is only half the battle. It is also necessary to determine policy on how the behavior of participants will be regulated to ensure that actual harvest is less than or equal to the allowable level. This is also a difficult process that involves issues of biological effectiveness, economic efficiency, and efficacy of enforcement. We turn to the second issue in the next chapter.

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Chapter 7

Economic analysis of fishery regulation

7.1 Introduction

The problem of fisheries management, which comprises the choice of a target stock size and a harvest time path to achieve or maintain it, can be a difficult and complex process. However, just as troublesome is the problem of fisheries regulation which comprises the determination of how to control harvest such that the desired and actual catches in any year coincide. One of the problems is that although the regulation objective can be stated in terms of annual catch, as was done in the previous sentence, a fishery is not a static phenomenon, as evidenced by the time-path trajectories discussed in the previous chapters. Things that happen in one period can have repercussions in the future. This is also true of regulations. Things that are done in one period can have effects on both the stock and fleet size that will affect the efficacy of current regulations and the general ability to control harvest in the future. In fact, it is so convoluted that it is hard to know where to begin to explain it.

To set the stage, consider the following simplified history, which draws heavily on the Commission on Ocean Policy Report, of how regulation to control annual harvest levels has evolved over time (see USCOP, 2004, 287ff). An important part of the story line is how participants reacted to the regulations, what effects this had on their efficacy, and then how regulation programs were modified to make corrections.

Of course in the beginning, fisheries were not managed at all. People could fish as they wanted. There was open access as the term has been used above. Early on, however, governments would require participants to obtain a permit for their vessels or gear. The permits were freely available for a nominal fee and their purpose was mainly for record keeping and perhaps in some cases to add to the government treasury. Although it was not a concern because they were freely available, the permits were nontransferable. You could not buy a permit from another person, but you could easily get one from the government. In profitable fisheries, this entry led to ever-increasing numbers of participants, as would be predicted from the above analysis, which put increasing pressure on the fishery resource.

If things got bad enough, managers would begin to place controls on the activity of the existing participants. There was no thought to challenge the accepted custom that any one should be free to fish if they so desired. It would have been unthinkable to limit the number of participants. Rather harvest was limited by using input controls such as specifying allowable types and amounts of gear and methods, and limiting available fishing areas or seasons. By restricting what operators can do, this type of regulation increases the cost of fishing and creates incentives to change fishing procedures so as to increase catch, given the constraints. This has the twofold effect of decreasing the biological effectiveness of the regulation and increasing the cost of fishing.

Managers also used output controls such as setting total allowable catches (TACs) or trip limits for individual fishermen. These management techniques create incentives for fishermen to develop different types of gear or to devise new methods that allow them to catch more fish in spite of the regulations, and to do so faster than other fishermen, before any overall limit is reached. Neither input nor output controls provide incentives for individual fishermen to delay or forgo fish harvest, because any fish not caught is likely to be taken by someone else.

The incentive to keep one's individual catches as high as possible, which is part and parcel of both input and output controls, creates an unfortunate game between managers and fishermen where the fishermen always have the last move. In response to each new measure designed to control the amount of fishing effort that they are able to produce, fishermen have incentives to develop new fishing methods that, although legal, allow them to increase their effort while abiding by the regulations. The resulting increase in harvest prompts managers to promulgate more restrictive measures, and fishermen to develop more ingenious methods to work around them.

For example, if managers limit the length of the boat, fishermen might increase the width if that would increase fishing power. Instead of trying to build boats and design equipment that can harvest efficiently, with total output controls, fishermen have incentives to do everything in their power to modify inputs to catch fish faster than their competitors do. If input controls are used, fishermen will work to get around the constraints. In the short run, such regulations can be biologically effective because it takes time for fishermen to adjust their gear or behavior. However, the temporary increase in stock size just helps to finance more changes in such things as boat designs with more fishing power. This phenomenon has been called "the race for fish."

In addition to conservation concerns, the race for fish can create safety problems. Faced with a sharply curtailed amount of time in which to harvest, fishermen may feel compelled to operate in unsafe weather conditions rather than forgo harvests to their competitors by waiting for fairer weather.

As a next step in the development of modern fishery management programs, managers started to control total catch or effort by limiting the number of participants through limited access programs. Although they are common now, they were very controversial when they were first implemented because they contravened the widely held belief that people should have the freedom to fish. These programs were commonly called *limited-license programs*. There are several important changes in the nature of the permits that were issued as part of limited-access programs. First, by definition, they were not freely available but were issued in limited numbers to specific participants, usually to a subgroup of current participants. (The distributional issues associated with limited-access programs are referenced in more detail below.) Second, instead of just a general permit to fish, they were normally a permit to operate a specific size and type of boat. Third, in most cases, they were transferable. If a person wanted to participate in a limited access fishery, it was necessary to buy a permit from a current owner. Finally, there were rules on how a permitted vessel could be changed with the sale of the permit or if an owner wanted to obtain a new boat. The real object was not just to limit the number of permits but to limit the ability of the permitted fleet to take catch.

However, these limited-license programs were just another type of input control where the input controlled was, the most basic of all, the fishing platform. In many cases, the status quo input or output controls remained in effect. In some instances, these limited-access programs were of little use because the number of permits did not place an effective binding constraint on the number of participants. In those cases where they did form a binding constraint, they did partially circumscribe the problem. At least there were a limited number of individuals who could join the race for fish or the race to improve the fishing power of their vessels. Depending on the actual number of permits relative to safe harvest limits, the types of other management controls, the potential for input substitution in the fishing process, and the rules for vessel modernization, a limited-access program could sometimes be effective for holding harvest at desired levels, at least for the short run.

Where the conditions were not right and harvest levels tended to continually exceed the desired levels under limited-access programs, a logical next step was to specify the access control in terms of output. New programs were instituted where the relevant permit was an entitlement to take a specific amount of harvest. This was quite a change. A permit to take a specific amount of catch was much less elastic in terms of what would likely be caught than a permit to operate a specific type of vessel. While it was still necessary to obtain a permit to operate a vessel, those permits were freely available. The controlling permit is the permit to harvest. These programs were first called *individual transferable quotas*, or ITQs, because for the most part, the permits to harvest were transferable. They are currently referred to, appropriately, as limited-access permits, or LAPs. In some cases, there were other controls on the way permits were used, such as transferability rules. Moreover, the harvest permits were issued in terms of a specified portion of the TAC. As opposed to limited-license programs that were input controls, ITQs were output controls.

With the assurance of a specified share of the TAC, incentives facing the participants now coincide with those of the managers. The incentive for fishermen

Table 7.1 Classification of fisheries regulation systems

Open access	Limited access	
Freely available permits	Limited number of permits	
Normally in term of vessels	Limited license programs Permits to operate specific type of vessel	ITQs or LAPS Permits to take specified amount of fish
Nontransferable	Transferable or nontransferable	
Reguation	Supplemental reguation	
Input control	Input controls	
Output control	Output controls Permit controls	

to fish harder and faster is replaced with an incentive to catch the full share at a low cost and sell the best quality fish at the highest obtainable price. This incentive can be channeled to even better results with transferability because participants are free to match a vessel's efficient capacity with the appropriate number of permits to harvest.

While the above short history is far too simplified to capture all of the nuances involved, it does provide the basics of the classification of fisheries regulation programs shown in Table 7.1. The two basic types are open access and limited access. Open access does not control the number of participants, and controls harvest by establishing input or output controls on participant behavior. There is an inherent conflict between the incentives of participants and the objectives of the harvest controls, and these can often cause problems with the biological and economic success of management.

Limited-access programs put controls on the number of participants, and do so in a way that imposes limits on harvest. Limited-license programs are input controls, and because they impose somewhat elastic constraints, other output or input controls are often used as a supplemental form of harvest control. They focus on effort and, as such, are subject to many of the weaknesses of pure open access. However, they offer the ability to place some binding constraints on total harvest; therefore, they do have the potential for some success. ITQs put controls on harvest, and if properly enforced, can be biologically effective. In addition, they provide economic incentives to take the limited amount of harvest as efficiently as possible. Because they are based on harvest, ITQs place a more strict constraint on participants, but they may also require some supplemental input or output regulations. Both limited licenses and ITQs will require other controls on the way the permits are used or transferred.

The transferability issue in limited-access programs deserves some clarification. In open access, it is not an operational issue, but the implications are important. The permit must be obtained from the government, but it is freely available to all on equal terms. By the very notion of limited access, transferability becomes an issue. If there are only a limited number of permits and the program is intended to last, then it is necessary to specify how the system will survive as participants retire and boats sink or need to be replaced. Transferability by sale or inheritance and vessel replacement according to specified rules is the most common choice. However, some would suggest that they be nontransferable on the basis that dispensing them is the proper role of government. According to this view, the permanent granting of the permits is not a proper use of a nation's natural resources. However, as it will be shown below, transferability can have important effects on the success of limited-access programs.

In addition to the comparison between open and limited access, a second way to classify regulation systems, which has its origins in the economics literature, is command and control versus the application of market principles. The former, as the name implies, specifies rules for the way in which production must be undertaken. The latter uses market incentives to control behavior. These incentives can be induced through either prices (taxes) or quantities.

For the most part, however, the two classification systems are equivalent. If there are supplemental controls under open access, which is almost universally the case, it becomes a command and control system through the regulation of the behavior of individual participants. With limited access, the fact that there are a limited number of permits, in terms of either effort or harvest, provides the basis for market-based management. Making the permits transferable clearly classifies them as market based.

Taxes are a market-based approach to management. While the theory of using taxes on fish is well established, for political and other reasons, they are almost never used. They do fit into this classification, however. ITQs are the quantity-based equivalent of taxes. The government issues the appropriate number of permits to obtain the desired harvest. Given that it can be enforced, the desired harvest will be taken. With taxes on fish, the government is essentially saying that anyone may have a permit to harvest as long as they pay the specified tax. The idea is to set that tax so that the amount of harvest that potential participants will be willing to take will match the desired harvest. While there is likely a one-to-one relationship between the amount of the tax and the amount that will be harvested, it is often hard to guess which tax level will bring forth the desired harvest. This is one of the other reasons that taxes are not often used as a fishery control device. The point here is that taxes do fit into our open access (command and control) versus limited-access (market-based) classification.

The purpose of this chapter is to describe in some detail the different possible types of regulations introduced above and, more importantly, to compare them according to biological effectiveness, economic efficiency, and distribution effects. Comparisons according to the last criterion are more case specific and only general comments will be possible.

The discussion makes use of appropriately modified versions of our simulation models. We use the disaggregated version because it can demonstrate the effect of regulations on vessel operation. For the ease of operation, we make use the Schaefer biological model, which is capable of producing the general results. The age-class model is used in the exercises given in the CD for comparison purposes and for looking at special regulations such as mesh and fish size restrictions.

As we proceed, it is important to remember the purposes and limitations of models, especially as the discussion moves toward practical applications. The models are based on restrictive assumptions that allow for the study of the essence of fishery operation in a rigorous manner. Every detail cannot be captured, however, because many complicating issues are put aside. It is always important to keep the explicit and implicit assumptions in mind when interpreting the results. In short, our models can be used to draw important conclusions regarding the expected results of different regulations. We take care to discuss the applicability of the results to more general situations. In addition to the normal reservations dealing with the use of models, our detailed models make use of specific assumptions with respect to the absolute and relative size of the economic and biological parameters. In some cases, the type of result which follows from the use of a certain regulation is sensitive to parameter selection.

It will prove useful to make comparisons using three different time horizons that are related to the nature of the assumptions. A large part of practical fisheries management is determining what to do to achieve a target harvest level in the coming season. This calls for a short-run analysis where the achievement of the target harvest level must be assessed in terms of current stock and fleet conditions. To put the discussion in the context of the uncertainty analysis introduced above, it may be best to think of status quo as really being the best estimate of the existing stock and fleet size and composition, where neither of them is at equilibrium level.

But the operation of a fishery is a dynamic bioeconomic process where a change in one part of the system will likely create changes in other parts. This calls for what will be called a *medium-run analysis* that traces what will happen to fleet and stock size as a result of the regulations. This involves making changes to the model by noting constraints on variables and/or revising the array of economic parameters so as to capture the effects of the regulation. This will produce changes in the population equilibrium curve (PEC) and the economic equilibrium curve (EEC), and hence in the bioeconomic equilibrium. This will also change the trajectory path that shows how the fishery adjusts from the status quo to the new equilibrium.

To understand the full implications of using various types of regulations, it is also necessary to take a long-run view and consider how the incentives for achieving technological change will be affected. Since technology is captured by the combination of cost and catchability coefficients, and these are assumed to be endogenous to our discussion, our model cannot be explicitly used to consider such issues. However, by noting how changes in these parameters are likely to change the results, it is possible to predict some general trends.

7.2 Introduction to regulation discussion

The remainder of this chapter will compare and contrast the various types of regulations that are used to control harvest. Remember, this is a different issue than selecting the desired or target harvest level. The issue here is what can be done to control the amount harvested by the existing fleet. For pedagogical purposes, the order in which the types of regulations are discussed will follow the order they were introduced in the simple history provided above. At the same time, to keep this in context, we begin by focusing more on the biological and technical aspects of regulation because this was, to some degree, the focus of early fishery management agencies. In the course of the discussion, we introduce the bioeconomic aspects of regulation to demonstrate how it allows for a better representation of the problem of controlling harvest. The notion behind this historical approach is to shed some light on why the fisheries of the world are in the state they are in and why there has been a paradigm shift in the way people are looking at management.

The discussion will be in the context of an example. This makes it easier to show differences between the different types of regulation. We will assume that our hypothetical fishery is at certain point on its trajectory. This is necessary because all regulation programs start with a given fleet and stock condition. We then assume that a target stock size and a harvest time path to achieve it have been selected. The immediate problem is to set regulations such that actual current harvest equals the target harvest. We start with a short-run approach and show why open access regulations that may appear to make sense using static regulations based on the status quo situation are not successful in the medium and long run. We then take a broader look at the regulation process recognizing that if managers find that regulations are not working over time, they will make adjustments. The distinction between the static regulations and sequential regulations is pedagogical, but it helps put important issues on the table. We recognize that most real-world regulation is sequential.

To start the discussion, assume that the stock size in our hypothetical fishery is currently 40,000 tons (X_0) and the fleet size is 12. At this stock size, the profit-maximizing amount of daily effort is 2.9 (see Equation 3.13), which results in a total level of effort equal to 5,220 and a harvest of 10,440 tons (y_0). Because fisheries are almost never in bioeconomic equilibrium, we have chosen a status quo that is a nonequilibrium point. This provides for a richer discussion but it necessitates being very clear about which results are sensitive to the starting point. It is assumed that the long-term fishery management goal is to achieve the maximum economic yield (MEY) stock size. Call this X_{tar}. This stock size will provide a sustainable harvest of 6,851 tons. For simplicity, assume that a constant target harvest path will be used. Therefore, there will be a target harvest level, call it y_{tar}, of 6,851 tons. As a point of reference, y_{tar} is 65% of y_0.

The bottom line is that the goal of the regulation program must be to cause the current fleet operating at the current stock size to reduce its harvest to y_{tar}. This is somewhat of an oversimplification, but it allows for a focused discussion. As will be clear below, while this will always remain the critical short-term decision of regulation, prudence requires that it be made taking into account wider implications, including the fact that the decision will have to be made again next year.

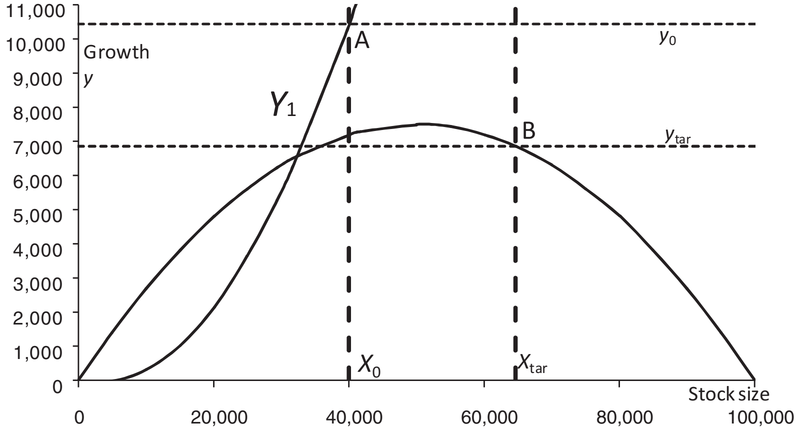

Figure 7.1 The relationship between the status quo and the target stock sizes.

The biological aspects of the status quo situation in terms of the Schaefer growth curve are pictured in Figure 7.1. Point A represents the status quo stock and harvest combination. The curve labeled Y_1, which goes through that point, represents the short-term yield curve for the existing fleet size. It shows how harvest would change if the same fleet operated over the range of stock sizes. Point B represents the target stock size and harvest level. Since the current harvest is above the sustainable yield curve, *if all else remains equal*, the stock size will fall and an equilibrium will be achieved where Y_1 intersects the sustainable yield curve. However, if harvest can be kept to y_{tar}, the stock will grow to X_{tar}.

We divide the discussion using the classification system in Table 7.1. We will turn first to open access regulations. The last main section in the chapter will cover limited access regulations. In both sections, we make distinctions between input and output regulations.

7.3 Open access regulations

7.3.1 Short run analysis

Consider the problem from the point of view of a management agency. In the short run, it must set harvest regulations in the status quo situation that will lead to an actual harvest of y_{tar}. The agency can use input controls such as closed seasons or gear restrictions, or output controls such as TACs or vessel trip limits. But, for practical purposes, it is important to understand what an agency can know and how it can determine specifically what it has to do once it has chosen a regulation type.

Let us consider this on a conceptual level first. The short-run fleet yield function is reproduced as Equation 7.1. Since the catchability coefficient (q) is a potential variable of regulation, daily effort is expressed as a function of X and

q (see Equation 3.13):

$$y_0 = \{V_0 D_{\max} f^*(X_0, q)q\} X_0 \tag{7.1}$$

Quite simply, if harvest is to be reduced, the values of the variables inside the {} parentheses will have to be reduced individually or in combination. At least that is the mathematical interpretation of the model. And it is a fairly good interpretation of the short-run task of fisheries management. If you want to control harvest, you have to control the number of vessels and/or the way the vessels operate.

Using the term E for aggregate effort (the product of fleet size, days fished, and the daily level of effort), the term in question can be expressed as qE, which is the fishing mortality rate, F (see Equations 3.5 and 5.20). To achieve the short-term harvest target, y_{tar}, the regulated fishing mortality, F_r, must equal:

$$F_r = \frac{y_{\text{tar}}}{X_0} \tag{7.2}$$

In terms of the above example, this means that at the existing stock size, the fishing morality rate must be restricted to 0.172 [6,851/40,000]. If there are no changes in q, this means that aggregate effort must be restricted to 3,425 [0.172/q]. This is a 65% drop in effort also. It is very difficult in the real world to calculate the necessary reduction in fishing mortality. The fact that under the status quo conditions, the required reduction in effort is proportional to the required reduction in fishing morality appears to provide some help. Let us take a look at how an agency might attempt to obtain the appropriate reduction in fishing mortality. We look at input controls first and move on to output controls.

7.3.1.1 Input controls

For the present, we assume that the view from the agency is as follows. We have a given stock and a given fleet size. If we can restrict harvest to y_{tar}, the stock will grow to our target level. So the first step is to achieve the y_{tar}. Historically, this has often been accomplished using input controls to *indirectly* control harvest. In terms of our model, the possible input controls are vessel limits, allowable fishing day (season control), controlling effort per day, or gear restrictions to reduce the catchability coefficient.

To use input controls, the specific regulations must be determined using a set of *specification equations*. While there is a wide range of possible procedures, an example is presented below. The regulated level of the input is the current level reduced by the ratio of the target yield to the current yield. The r subscript refers to the regulated level of the variable. Of course, these equations are not identical to Equation 7.2, but y_0, the size of which will be known, does carry information on current stock size. Understanding the problems that result from basing regulations on static conditions is one of the goals of this discussion:

$$V_r = \left[\frac{y_{\text{tar}}}{y_0}\right] V_0 \tag{7.3}$$

$$D_r = \left[\frac{y_{\text{tar}}}{y_0}\right] D_{\max} \tag{7.4}$$

$$f_r = \left[\frac{y_{\text{tar}}}{y_0}\right] f^*(X_0, q) \tag{7.5}$$

$$q_r = \left[\frac{y_{\text{tar}}}{y_0}\right] q \tag{7.6}$$

All four of the variables have been included for completeness. Note that the first equation would control the number of participants while the others control the activities of the individual vessels. But early in the history of fisheries management, controlling the number of vessels was not a viable option. It was not considered fair, and to some extent, it was not considered necessary. We discuss vessel limits, sometimes called limited-license programs or limited entry, in more detail below.

Look at the other three equations in the context of what a real-world agency can do. Equation 7.4 can readily be used because agencies have information on current season length. This equation, or some more sophisticated variant, is regularly used to estimate the required restricted season length to achieve a target harvest level. Even in the short run, the degree to which it will be successful will depend on how easily other inputs can be used to substitute for the limit on the number of days fished.

Equation 7.5 could be used in those cases where there is information on daily effort. Limiting time on the fishing grounds is not a commonly used regulation because it is often hard to enforce. But it is a technical possibility.

The last equation requires a little more explanation. In the first place, while it is analogous to the others, there are theoretical differences. A decrease in q will lead to a decrease in the profit-maximizing level of f, and so Equation 7.5 will overestimate the required reduction in q. Even ignoring that, it cannot be readily used by agencies because they do not have information on how q is determined. However, agencies frequently use gear restrictions to change q. To understand how this works, it will be useful to provide a more detailed discussion of the relationship between daily effort, the catchability coefficient, and cost. Daily f is measured in terms of hours of fishing per day; hence, the product of VDf, which is aggregate effort, is measured in terms of hours of fishing per year. The catchability coefficient is the constant which translates hours of fishing into a fishing mortality rate.

But conceptually, where does q come from? The harvesting power of a certain amount of time of fishing depends on the type, size, and technology of the boats, how they are deployed in space and time, the types and amounts of gear in use, the size selectivity of the gear, the amount of navigation and fish-finding equipment, crew size, the skill of the captain and the crew, and their knowledge of stock behavior and location. At the same time, many of these things affect the parameters of the vessel cost function.

In brief, the choice of the types, combination, and levels of inputs and activities used simultaneously determine q and the cost parameters. And participants can be assumed to make this choice such that the catchability coefficient and cost parameters produce the highest profits over the relevant range of stock sizes. At the same time, there will be incentives for developing innovations in terms of new types of inputs or fishing activities or ways of combining them to increase profitability.

An important auxiliary point is that the incentives for technological innovation will not cease with the introduction of gear restrictions. In fact, the untoward effects of the restrictions may provide a spur for innovations that try to legally sidestep the regulations. This has two effects. First, over time the efficacy of the restrictions may be offset by the induced innovation. Second, the innovations that make sense under the restrictions may be perverse when viewed from a broader perspective. For example, a restriction on vessel length may make a vessel of twice the normal width an attractive alternative, when such a vessel would never be considered otherwise because of cost, seaworthiness, or other issues.

This conceptual picture of the relationship between effort, q, and costs, while too complex to be included in our model, provides a framework for understanding how gear restrictions can affect fishing behavior. This type of regulation places limits or restrictions on the types, combinations, and levels of inputs and activities such that q will decrease. Examples include limits on vessel and crew size, engine power, and the use of particular inputs. Also, fishing may be prohibited in certain areas. Such regulations will affect the catchability coefficient and may affect the cost parameters.

While it is a simple matter to use Equation 7.6 to calculate the necessary reduction in q such that harvest will be restricted to the target level, it is much more difficult to accomplish this in the real world. For one thing, unlike the nominal aspects of fishing effort like season length, it is more difficult to determine what needs to be done to achieve a specified reduction in harvest. In some cases, there may be a linear or semilinear relationship between how many times an activity is performed (the set and retrieval of the net) and how much is caught. More often, however, this is not the case. In addition, as mentioned above, there are usually a number of ways that things can be done, and so limits on certain inputs or activities can be mitigated by changes in others. It is very difficult to predict how regulations or restrictions on various inputs or activities will affect q, and hence harvest.

7.3.1.2 Output controls

While the above set of specification equations is in terms of input controls, it is also possible to restrict harvest with output controls. One way is to use trip catch limits which stipulate the maximum amount that a vessel can land on any trip. In the context of our model, each fishing day is equivalent to a trip. The analogous specification equation for a trip limit is:

$$TL = \frac{y_{\mathrm{tar}}}{[D_{\max}\, V_0]} \tag{7.7}$$

If vessel output per day is limited to TL, as calculated in Equation 7.7, the annual total harvest from V_0 vessels fishing $D_{\max}$ days will equal y_{tar}.

While it may not be obvious, the trip limit is the flip side of a control on f. The catch per day for a vessel is equal to $qXf^*(X_0, q)$; therefore, given the TL specified in Equation 7.7, a vessel will have to stop fishing each day according to the following equation:

$$f_{\mathrm{tl}} = \frac{y_{\mathrm{tar}}}{[V_0\, D_{\max} q\, X_0]} \tag{7.8}$$

Multiplying top and bottom of Equation 7.7 by $f^*(X_0, q)$ and simplifying shows that it is technically equivalent to Equation 7.5. However, they will only be operationally equivalent in the short run; they will have different long-term effects, which will be explained below.

While trip limits and controls on daily effort are theoretically analogous, at least in the short run, there are differences with respect to enforcement. Trip limits may have an advantage because catch per day can be measured, and therefore they are easier to enforce than restrictions on daily effort, which is harder to measure. Further, a regulation that focuses on output will be more likely to achieve the output goal. A more comprehensive discussion of enforcement is best postponed until a better stage is set.

Another output control is to set a TAC equal to y_{tar} and then prevent any further fishing when harvest reaches that level. This is the flip side of regulation on season length. With the latter, the fishery must shut down after the specified time limit and the allowable harvest is whatever is taken. With a TAC, the limit is on the harvest, and the season length is whatever is necessary to take that limit.

But in the short run, they will both produce the same results. This can be demonstrated as follows. Setting the short-run catch equation equal to y_{tar} and solving for D obtains the number of days the fishery would be open under a TAC program:

$$D_{\mathrm{TAC}} = \frac{y_{\mathrm{tar}}}{[V_0\, f^*(X_{0,} q) q] X_0} \tag{7.9}$$

Multiplying top and bottom of the right-hand side of Equation 7.9 by $D_{\max}$ produces a result that is identical to Equation 7.4.

So in the short run, theoretically there is no difference between a season control based on the above specification equations and a TAC program. They both will produce the same season length. To anticipate the discussion below, one difference is that in the long run, a constant TAC does not require an annual specification equation. If the TAC can be enforced, proper season length falls out automatically. This endogenous feature is important for long-term success.

At another level, there are also differences with respect to enforceability. It is often easier to control season length than to track harvest on a fleet-wide basis and then close the fishery before the TAC is surpassed. However, to the extent that it can be enforced, a TAC will guarantee that harvest is kept to the stipulated level. Seasons may be easier to enforce, but if vessels can use more inputs (fish harder) during the closed season, the target catch may be surpassed. In the medium or long run, there are more differences between these two types of regulations, and this will be described in more detail below.

There is no output-based equivalent of gear restrictions to affect q.

In summary, even from a very short-run point of view, establishing actual input regulations that will obtain the desired reduction in harvest is a difficult task. For one thing, in the real world it is difficult to know exactly how a regulation will affect harvest. This is true even for controls on things that appear to be linearly related to harvest such as season length. Vessel operators can counteract the intended effect of a regulation by increasing the use of activities or inputs that are not restricted. Things get even tougher when the input–output relationship is nonlinear or unknown. Gear restrictions are a very rough tool indeed. A TAC, the most commonly used output control, does perform better to the extent that it can be enforced. Trip limits face potential problems if the number of participants can change easily.

7.3.1.3 Analysis

Let us take a look at the implications of static regulations based on current conditions, as illustrated in the above specification equations. Assuming that these regulations can be implemented, how will each of them affect the operation of our hypothetical vessel? This has both short-run and long-run implications. How will the effects on individual vessels affect the bioeconomic operation of the fishery? An important item to note, and one which is sometimes lost in biological discussions of regulations, is that while theoretically all these regulations can achieve the same short-run change in harvest, there will be different effects on vessel costs and hence on profits.

Table 7.2 can be used to focus the discussion. The status quo levels of D, f, and q are shown in the first row. (For simplification, the values have been rounded off.) The required regulated values for the variables, as calculated using the specification equations, are shown in the remaining rows. For example, the estimated season length that will limit harvest to y_{tar} is 98 days. As noted above, a regulation which affects q can quite easily affect costs as well. To include this in the analysis, two cases are considered. In the first, it is assumed that costs are not affected, while in the second it is assumed that there is a 10% increase in the c_s, the slope of the marginal cost of daily effort function. It is likely that measures to change q will in fact change the cost parameters, but separating out the two effects is useful. The table also contains information on how vessel revenues, costs, and profits are affected by these specific regulations. These values can

Table 7.2 Comparison of the economic effects of different regulations that accomplish the same short-run biological goal.

Regulation type	D	f	q	TR	VC	Profit	Change in profit
Status quo	150	2.9	0.00005	\$14,790	\$8,483	\$3,308	
D	98	2.9	0.00005	\$9,711	\$5,570	\$1,142	−\$2,166
f	150	1.9	0.00005	\$9,711	\$4,147	\$2,564	−\$744
q	150	1.7	0.000033	\$5,794	\$3,546	−\$752	−\$4,060
q with cost increase	150	1.6	0.000033	\$5,267	\$3,224	−\$957	−\$4,265

be calculated easily using the microeconomic analysis of vessels provided in the exercises for Chapter 3 given in the CD. All of the regulations result in a decrease in profits, although the actual decrease varies.

Let us consider the required changes in D and f. Because both regulations reduce harvest by the same amount, both produce the same reduction in revenue. They do have different effects on cost, however. In the case of a restriction on D, variable costs will fall by the same proportion as the reduction in D. Fixed costs will remain the same, and since variable costs will fall by a smaller absolute amount than will revenue, net returns will show an absolute decline. Given our assumptions, the restriction on D will have no effect on f, the daily amount of effort. There is no incentive to change f from the status quo level because the marginal revenue (PqX) and the MC of f have not changed (see Figure 7.2, which is the same as Figure 3.4, except that the marginal revenue line is set using the status quo stock size).

To see why an analogous restriction on f will have a different effect on costs, consider Figure 7.2 again. Given the parameters, the vessel will want to produce 2.9 units of effort per day but will be allowed to produce only 1.9. The explanation of the larger reduction in cost is related to the increasing marginal cost of producing daily effort. Since effort is reduced evenly on all fishing days, the allowable effort can be produced more economically by avoiding the higher marginal costs when more effort is produced per day.

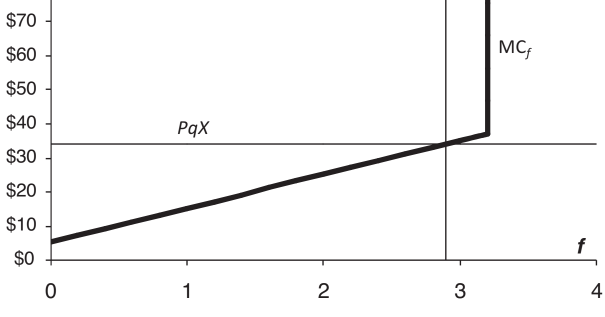

Figure 7.2 Marginal revenue and marginal cost for daily effort.

Note that while restrictions on D will not have any immediate direct effect on f, because of the MR = MC criterion, the reverse logic does not necessarily hold. D is assumed to be set at $D_{\max}$. But, while vessels may be content to fish 6 days a week under normal conditions, they may well start fishing on Sunday if restrictions on daily effort put the financial health of the boat in jeopardy.

Gear restrictions that affect q will have interrelated effects on other aspects of fisherman's behavior, which, while they are obvious from the economic analysis, are not often considered in normal fisheries management discussion. Consider Figure 7.2 again. A reduction in q means that there will be less catch per unit of effort. This is the predicted (or semipredicted) reduction in harvest. But this will simultaneously reduce the marginal return for f, and it may affect the marginal cost of f, which will change the profit-maximizing level of f and cause an unpredicted further reduction in harvest. The full effects are shown in Table 7.2. The required change is to reduce q to 0.000033. However, at the status quo stock size, this will cause f to fall to 1.7. The dual effects on harvest cause the reduction in revenue to be greater than with the analogous short-run changes in D and f. The effect is even more pronounced with the increase in the cost parameters because f falls even further. There is a larger reduction in nominal effort which means that the reduction in variable costs is larger in this case, but the net effect is still a larger reduction in net profits.

7.3.2 Medium run analysis

Implementing any of the regulations listed in Table 7.2 will lead to an immediate reduction in harvest such that the actual harvest will equal y_{tar}. The reduction in harvest will actually be larger in the case of gear restrictions. That is, all else equal, using the specification equations individually will reduce aggregate effort or change q such that the required level of fishing mortality for the status quo stock size is achieved or surpassed. The problem is that *shortly* after they are implemented, things will begin to change such that neither the desired harvest nor the target stock size will be achieved. In addition, there are frequently other unintended changes as well. This is a very important conclusion for understanding the difficulties involved in fisheries regulation, and more of the logic to support it will be provided in the discussion to follow.

Let us turn to the medium-run implications of traditional harvest regulations. To understand these effects, a full bioeconomic analysis is necessary because fishermen will operate under the same incentives. Their regulated behavior will produce different results, and in most cases, the results will be different than intended. This can be demonstrated using a regulated open access model.

To begin, consider Figure 7.3, which depicts the status quo situation in the context of our model which shows the predicted trajectory of the fishery. Point A represents the status quo stock and fleet combination. The policy choice in our hypothetical case is to achieve a target stock size of X_{tar}. In the real world, the effects on fleet size often are not a main policy consideration. But for reference in this discussion, Point B is at the fleet size which can harvest the

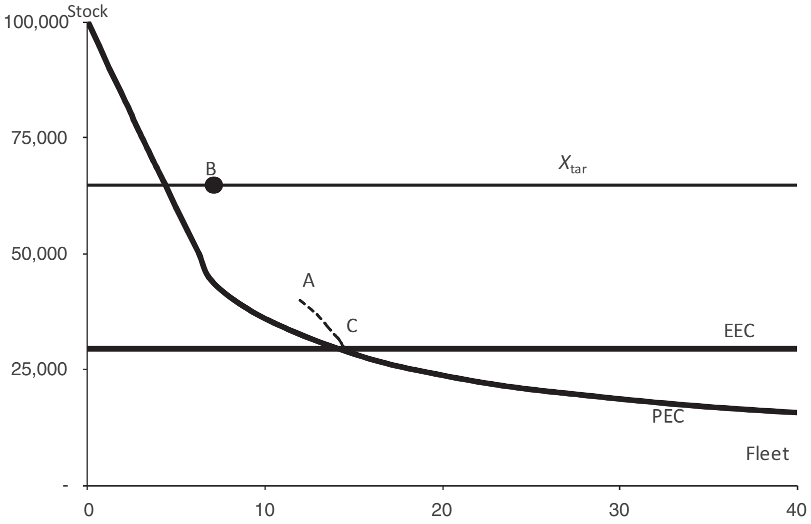

Figure 7.3 Trajectory from status quo stock and effort combination.

sustainable yield from X_{tar} at the lowest long-run cost. We will return to the implications of this below.

As shown by the trajectory line, all else equal, the status quo bioeconomic equilibrium will ultimately be achieved at point C. Recall that the trajectory curve is calculated using Equations 3.26 and 3.27. If point A is "where we are," point C is "where we are going." The policy implications of this more complete picture of the status quo are important. While we may be aiming for a fixed target (point B), the position from which we will be moving from is almost surely changing. This is one of the reasons why the predicted effects of the regulations will be incorrect.

In this particular case, the status quo trajectory moves in an SE direction; the stock will decline and the fleet will increase. Depending on the position of the status quo point relative to the EEC and the PEC, the trajectory could be aiming in any direction. All of the possible cases will not be discussed because the important points can be covered using this one case. Other cases will be included in the exercises in the CD for this chapter.

Before going on, it will be useful to interpret the figure in the context of a broader picture of real-world fisheries management. There is uncertainty about the actual location of points A and C. The current stock condition and the predictions of future stock and fleet growth are only estimates. In addition, firms are continually working to develop better technology so as to improve profits. These changes in the cost and catchability coefficients will change the shape and position of the EEC and the PEC. In general, they will tend to lower the EEC (firms will be able to operate profitably at lower stock sizes) and shift the PEC in an SW direction (it will take fewer vessels to harvest the sustainable yield from any stock size). This means that the task of fishery management is made even more difficult because point C is continually moving away from point A.

In the real world, there are many variables that can be regulated to control harvest. However, in the context of our model, we can control f, D, q, or the cost parameters. But the basic principles and general results can be well explained using this set by noting how the shape and position of the PEC, the EEC, and the trajectory curve are changed. And the interesting thing is that changes in f, D, or q that are predicted to have the same effect on current harvest according to the specification equations will have different effects on the curves.

As a point of reference, the equations for the EEC and the PEC are reproduced below (see Equations 3.17 and 3.25).

$$\text{EEC} \quad X = \frac{\left[c_i + c_s f_{\min} + \frac{FC}{f_{\min} D_{\max}}\right]}{Pq} \tag{7.10}$$

$$\text{PEC} \quad V = \frac{G(X)}{[D_{\max}\, q X f^*(X)]} \tag{7.11}$$

This is a good time to point out an important difference in the two equations. The daily level of effort is in both of them but in different forms. The EEC uses $f_{\min}$, the level of daily output where the average cost of the vessel is minimized, because that is the level that is necessary to obtain an economic equilibrium. On the other hand, $f^*(X)$ is used in the PEC because it is necessary to consider how f varies with stock size in order to get an accurate accounting of the required fleet size. To anticipate the argument below, this is important for the analysis of the effects of regulation because both $f^*(X)$ and $f_{\min}$ can be affected by certain regulations.

From the EEC equation, it is clear that the only way to achieve an increase in the equilibrium stock size is to increase the long-run equilibrium cost of effort or decrease efficiency by lowering the catchability coefficient. Both will increase the cost per unit of harvesting fish (see Equation 3.17). Ultimately when fisheries managers talk about season closures, trip limits, etc., what they are really talking about are ways to make it more costly to catch fish.

Changes in the PEC are also related to efficiency as well. While the EEC speaks more about the equilibrium stock size, the PEC is about fleet size. Movements to the right mean that it will take more vessels to take the sustainable harvest from a given stock size.

The regulation trajectory curve will still be based on Equations 3.26 and 3.27, except that they must be modified by changing the variable that is affected by the regulation. For example, with a season regulation, $D_{\max}$ will be replaced by D_r.

In general, all of the regulations will move the EEC up (the minimum stock size at which vessels can operate at a profit will increase) and the PEC will shift in NE direction (it will take more vessels to harvest the sustainable yield from any stock size). While each regulation will have different effects (sometimes quite different), they will all increase equilibrium stock size and tend to increase fleet size. The increase in stock size will not, however, be as large as predicted.

Let us proceed with a detailed analysis of the various regulations. To facilitate the discussion, in each case, we will present a graph that shows how the regulation will affect the PEC, EEC, and trajectory curves. The open access curves will be solid and they will be referred to as the standard curves. The regulation curves will be dotted.

Table 7.3 summarizes the medium-run results of introducing the different types of regulations. In each case, they show the effect of controlling the variables in the shaded cells to the specified level. The equilibrium values of the other variables are shown in the other cells in the row. The first two rows show the status quo and the open access equilibrium while the third row shows the conditions that would exist if the target stock size could be achieved by an efficient fleet. These are included as reference points. The next six rows show the effects of the input and output controls discussed above. The other rows will be explained below. Note that while the static regulations were designed to reduce harvest such that, all else equal, the stock would increase to X_{tar}, none accomplishes that goal. Further, although they all were designed to do the same thing, the results differ.

Focusing the discussion on why this is the case will help explain the complexities of fisheries regulation. In order to complete this discussion, we will take a more general view of how to design regulations below.

7.3.2.1 Input controls

7.3.2.1.1 Season length

Figure 7.4 shows the effects of setting the season length to 98, the static season limit designed to achieve X_{tar} (see the fourth row in Table 7.3). By observing Equations 7.10 and 7.11, it can be seen that the decrease in D from $D_{\max}$ will shift the EEC up and the PEC upward and to the right. For the moment, ignore the heavy solid curve. The regulation trajectory will be based on equations 3.26 and 3.27 with the changes required due to the regulations. In this case, it will differ because the reduction in D will lower catch, and so the stock will not fall as fast as before. At the same time, it will reduce profits and so the absolute change in fleet size will fall as well. In this case, the regulated bioeconomic equilibrium will occur at point D, where there is an increase in both stock and fleet size compared to the open access equilibrium. Given the way the curves shift, stock size will always increase, but depending on the relative shift of the PEC, the fleet size could increase or decrease with a season length control.

How can we interpret the success of this particular regulation program? In the strictest sense, given that the goal is to move from point A to point B, a movement to point D might be considered a failure. The final operating combination of fleet and stock sizes is moved in the opposite direction. In fact, observers of the status quo situation might not be able to perceive any effect from the regulation. All they would see is a slight deviation in the trajectory. However, the bioeconomic analysis adds another perspective that tempers this evaluation. In one sense, the comparison should be between point C, the original bioeconomic equilibrium, and point D, the regulated bioeconomic equilibrium. Using this comparison, it can be concluded that the regulation was a relative biological success because equilibrium stock size did increase, although it did not achieve X_{tar}.

Table 7.3 Medium-run results of different types of regulations.

	X	V	Catch	D	f	q	y/D	Total E	$F = Eq$	Cost of E	Cost of fish
Status quo	40,000	12.00	10,440	150	2.90	0.000050	5.80	5,220	0.261	\$26.40	\$13.20
Open access	29,412	14.12	6,228	150	2.00	0.000050	2.94	4,235	0.212	\$25.00	\$17.00
Target	64,706	7.06	6,851	150	2.00	0.000050	6.47	2,118	0.106	\$25.00	\$7.73
Static *D*	34,928	16.07	6,819	98	2.47	0.000050	4.31	3,904	0.195	\$29.69	\$17.00
Static *f*	29,441	14.83	6,232	150	1.90	0.000050	2.80	4,234	0.212	\$25.02	\$17.00
Static *q*	44,820	16.82	7,419	150	2.00	0.000033	2.94	5,045	0.166	\$25.00	\$17.00
Static *q* with cost increase	46,570	17.08	7,465	150	1.91	0.000033	2.91	4,885	0.160	\$25.98	\$17.00
Static trip limits (3.8)	29,412	14.12	6,228	150	2.00	0.000050	2.94	4,235	0.212	\$25.00	\$17.00
TAC	64,706	24.00	6,851	28	3.20	0.000050	10.35	2,118	0.106	\$55.00	\$17.00
Sequential *D*	64,706	24.00	6,851	28	3.20	0.000050	10.35	2,118	0.106	\$55.00	\$17.00
Sequential *f*	64,706	33.82	6,851	150	0.42	0.000050	1.35	2,118	0.106	\$55.00	\$17.00
Sequential *q*	64,706	15.53	6,851	150	2.00	0.000023	2.94	4,659	0.106	\$25.00	\$17.00
Sequential trip limits (1.35)	64,706	33.82	6,851	150	0.42	0.000050	1.35	2,118	0.106	\$55.00	\$17.00
Limited license	41,101	7.87	7,262	150	2.99	0.000050	6.15	3,534	0.177	\$26.65	\$12.97
ITQ	64,706	7.06	6,851	150	2.00	0.000050	6.47	2,118	0.106	\$25.00	\$7.73

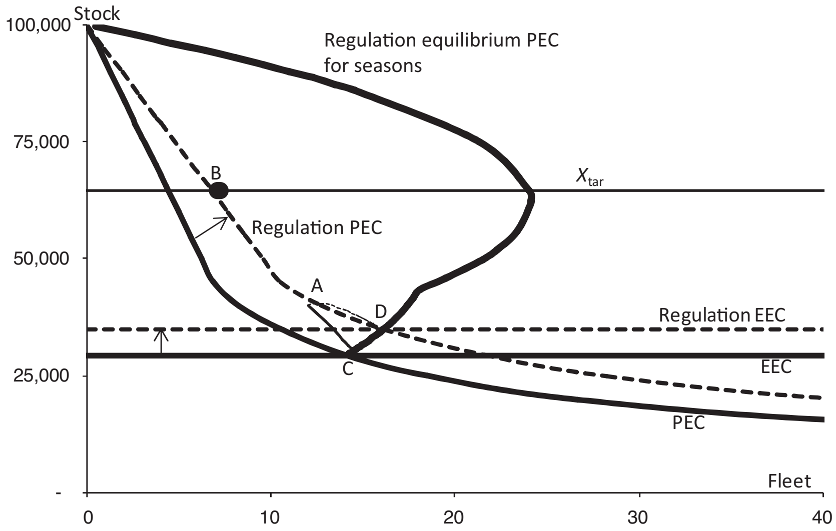

Figure 7.4 Change in PEC, EEC, and trajectory for season length control.

But why did the specified season length not achieve X_{tar} when that was what it was calculated to do according to the static specification equations? It will be illuminating to answer that question from two perspectives. First, let us look at what it did accomplish and why. From the point of view of the fishery operating at the status quo point, restricting the number of days fished reduced harvest and vessel profits (see Table 7.2). However, profits were still positive and so the fleet continued to expand, albeit at a slower rate. In addition, the restriction on days fished changed the cost structure of the vessels. It changed both f_{min}, the level of daily effort that will cause the boat to operate at the minimum of its AC curve, and C^*_E, the cost of operating at that point (see Equations 3.9 and 3.10). Because of the change in C^*_E, the bioeconomic equilibrium occurs at a higher stock size than it would have otherwise.

While that explains what did occur, how can we explain why it missed the target? There are two reasons. First, the level of D was selected so that the existing fleet operating at the current stock size would produce the level of E that will result in the target harvest. However, the regulation trajectory shows that the target level of total effort will not be achieved. The fleet size is going up. In addition, stock size is going down which means that the profit-maximizing level of f is decreasing. The changes in V and f will counteract the forced reduction in D.

In the second place, the target level of aggregate E that follows from the specification equations is not the proper target even if it could be achieved. The change in X means that the level of E that will achieve y_{tar} will change as well.

In summary, the static regulation will fail for two reasons, both related to the inherent dynamic changes in a fishery. First, it will not maintain the desired level of fishing mortality because nonregulated variables will change. Second, because stock size will change, the desired level of fishing effort will prove to be

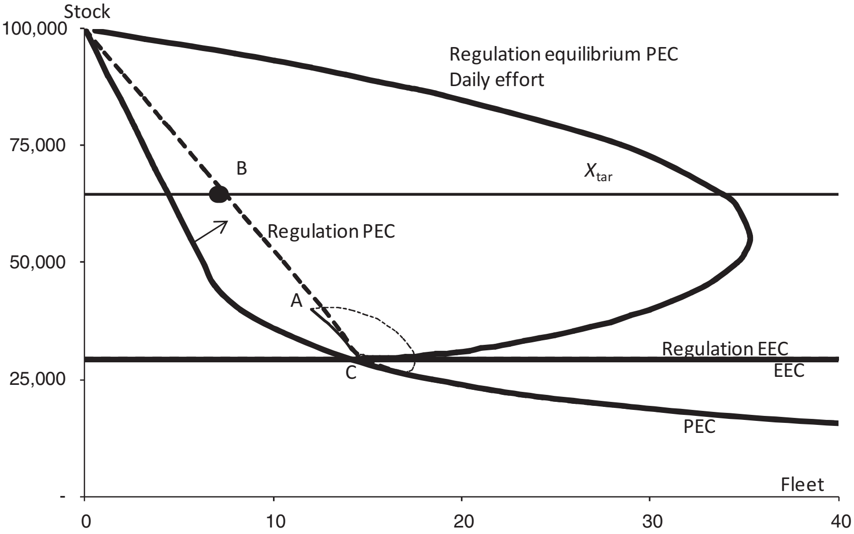

Figure 7.5 Change in PEC, EEC, and trajectory for controls on daily effort.

incorrect. The exact location of the regulated equilibrium will depend on how the variables change over time. In this case, the regulated equilibrium catch is below the target harvest, but the equilibrium stock size is less than the target stock (see Table 7.2).

7.3.2.1.2 Regulation on f

Figure 7.5 demonstrates the effects of limiting the amount of f that can be produced to 1.9, as specified by the static specification equation (see the fifth row of Table 7.3). Again, ignore for the moment the thick curve that is concave to the origin. The basic results with respect to success in achieving the targets apply in this case as well, but there are other interesting aspects, including the issue of regulations as binding constraints.

While there are significant changes in the PEC, the EEC hardly changes at all. The end result is only a very small change in the bioeconomic equilibrium point. The reason for small change in the EEC is that while the required reduction in f is large relative to the status quo amount (2.9 down to 1.9), it is small relative to $f_{\min}$, the open access equilibrium amount (2.0 down to 1.9) (See Table 7.2). Vessels will be forced to operate to the left of the minimum of the vessel AVC, because they cannot operate at $f_{\min}$. However, the restriction is insignificant and there is only a small increase in C_E. There is only a very small (imperceptible in terms of the figure) upward shift in the EEC. If the reduction in f required to achieve the short-term goal is such that the regulated f is less than $f_{\min}$, there will be no effect on the EEC at all. We will return to this point below.

The change in the PEC can be explained as follows: With the regulation, the maximum f will be 1.9 instead of the full capacity level of 3.2. The flat portion of the PEC will shift to the right because it will take more vessels to take the same amount of catch. In addition, the flat portion will exist over a longer range. The curved part will not begin until that stock size where $f^*(X)$ equals 1.9, and after that point, the old and new PECs will be coterminous.

While there is only an almost imperceptible change in the equilibrium, there is considerable difference in the regulation trajectory. Early in the transition period to the regulated equilibrium, the restriction on f will be a binding constraint on what the boats would have otherwise produced with the result that the stock will not fall as fast as before. As the stock size decreases, the regulation proves to be less and less of a binding constraint and the regulated equilibrium occurs very close to the open access equilibrium.

When compared to the status quo point, the increase in vessels counteracts the decrease in f, and the desired reduction in aggregate E is not achieved. The regulated bioeconomic equilibrium stock size will be less than the target.

This case demonstrates another reason why static regulations will not work sometimes; constraints that are binding at the status quo point may not be binding at other stock sizes. This is an extreme case because some f constraints can cause significant changes in the equilibrium. But as with restrictions on D, the results will not be as predicted by a short-run analysis and changes in stock and fleet size will counteract the restriction on f.

7.3.2.1.3 Regulation on q

Figure 7.6 shows the effects of implementing the static regulation on q, shown in Table 7.3, in the case where there are no changes in cost coefficients. The same general pattern is observed. The PEC shifts to the right because with the lower technical efficiency, more vessels are necessary to take the sustainable yield for

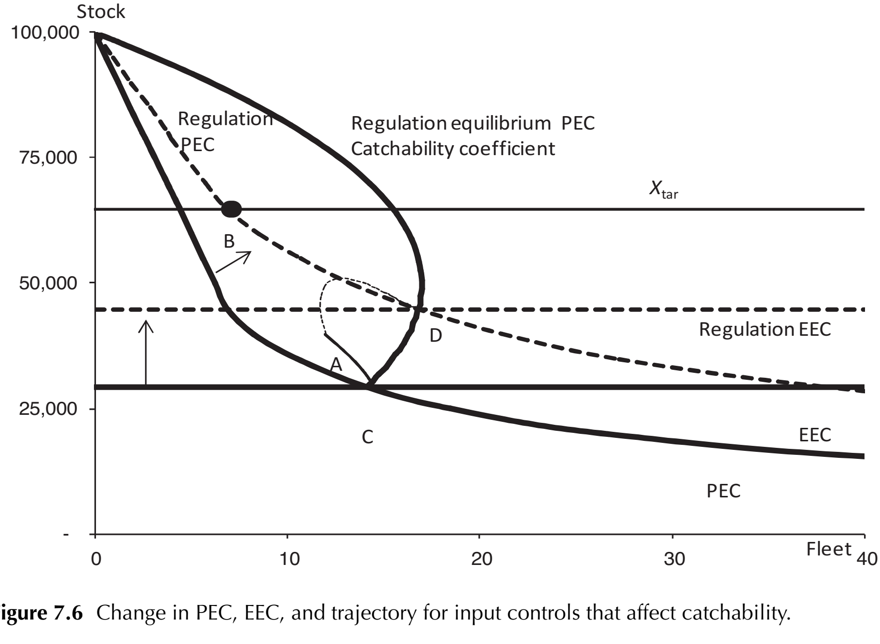

Figure 7.6 Change in PEC, EEC, and trajectory for input controls that affect catchability.

any given stock size. The EEC shifts up because with the lower efficiency, vessels can only earn positive profits at a higher stock size.

In this case, there is quite a change in the trajectory. As opposed to the control on season length, this regulation will counter the thrust of the status quo trajectory. The regulation immediately changes vessel short-run profits from positive to negative. As a result, vessels will initially exit and the reduction in harvest will cause the stock size to increase. This increase in stock size will increase harvest and when the profits become positive again, the fleet size starts to increase again. As a result, some of the short-run gains in stock size are lost. The regulated equilibrium shows an increase in both fleet and stock size as compared to both the open access equilibrium and the status quo. But again, the target stock size is not achieved.

While the short-term effect of the regulation on q was a reduction in f, note that at the regulated equilibrium, daily effort is the same as in the open access equilibrium (see Table 7.2). The reason for this is that in this case, the cost coefficients do not change. The bioeconomic equilibrium occurs when vessels are forced to operate at the minimum of their AC curves. Since cost conditions have not changed, at the equilibrium the boats will still produce the same amount of effort at the same cost level. However, given that the regulation reduces efficiency, the time spent fishing will result in less harvest. In the more likely case where this regulation will also affect cost, there will also be an efficiency effect. Not only will effort be less productive in taking harvest, it will cost more to produce.

The equilibrium level of f does not change, but the dynamics of achieving the regulated bioeconomic equilibrium results in an increase in the fleet size with the net effect that the aggregate effort is only slightly less than the status quo amount. However, given the reduction in q, the end result is a reduction in fishing morality, and the equilibrium stock size is higher than the status quo level.

Of the three static regulations discussed so far, all of which were designed to achieve the same thing, given the relative sizes of our parameters the regulation on q provides for the largest increase in stock size. One of the reasons is that the specification equation does not take into account the interrelated short-run effects on f, and hence will call for a larger reduction in q than the one that would be truly comparable to the other regulations.

7.3.2.2 Output controls

7.3.2.2.1 Trip limits

The economic analysis of trip limits is somewhat more complex than the input controls discussed so far. For one thing, it is necessary to transpose the output control into our analysis of vessel behavior that focuses on inputs. In addition, it will be necessary to confront the issue of when trip limits will pose a binding constraint on vessel operations.

Trip limits affect how much daily effort a vessel will be allowed to produce. It will depend on stock size and the specific trip limit (TL) according to the following equation:

$$f_{\text{tl}}(X) = \frac{\text{TL}}{qX} \tag{7.12}$$

The basic effects of trip limits can be demonstrated by substituting Equation 7.12 into the equations for the PEC, the EEC, and the trajectory curve. In order to do so, it is necessary to consider the relationship between $f^*(X)$ and $f_{\text{tl}}(X)$. A trip limit will only be a binding constraint over that range of stocks sizes where:

$$f_{\text{tl}}(X) < f^*(X) \tag{7.13}$$

This means that the operational level of f under trip limit regulations will be:

$$f_{\text{tl}}^*(X) = \text{Min}\left[f_{\text{tl}}(X),\ f^*(X)\right] \tag{7.14}$$

This is displayed graphically in Figure 7.7. The function $f^*(X)$ is monotonically increasing in X until $f_{\max}$ is reached (see the discussion around Equation 3.13. On the other hand, for any given TL, $f_{\text{tl}}(X)$ is a monotonically decreasing function of X. At higher stock sizes, it takes less effort to produce any given TL. The curve will shift up with an increase in the TL and vice versa.

Obviously, the level of the TL is of crucial importance. The catch per day for various stock sizes is listed in the eighth column in Table 7.3. Of particular interest is the catch per day at the open access stock size because a trip limit will have to be below this level in order to impose a binding constraint on the equilibrium operation of the fishery. The catch level at the status quo X_{BE} is the one that was used to generate the $f_{\text{tl}}(X)$ curve in Figure 7.7. To the right of the intersection of the two curves, the trip limit will be a binding constraint, and as such it will affect the trajectory curve. But it is only when the curves intersect

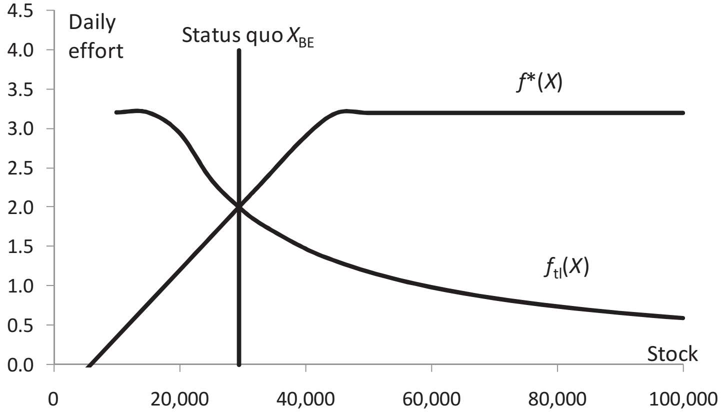

Figure 7.7 Range of stock sizes where trip limits will be binding constraints.

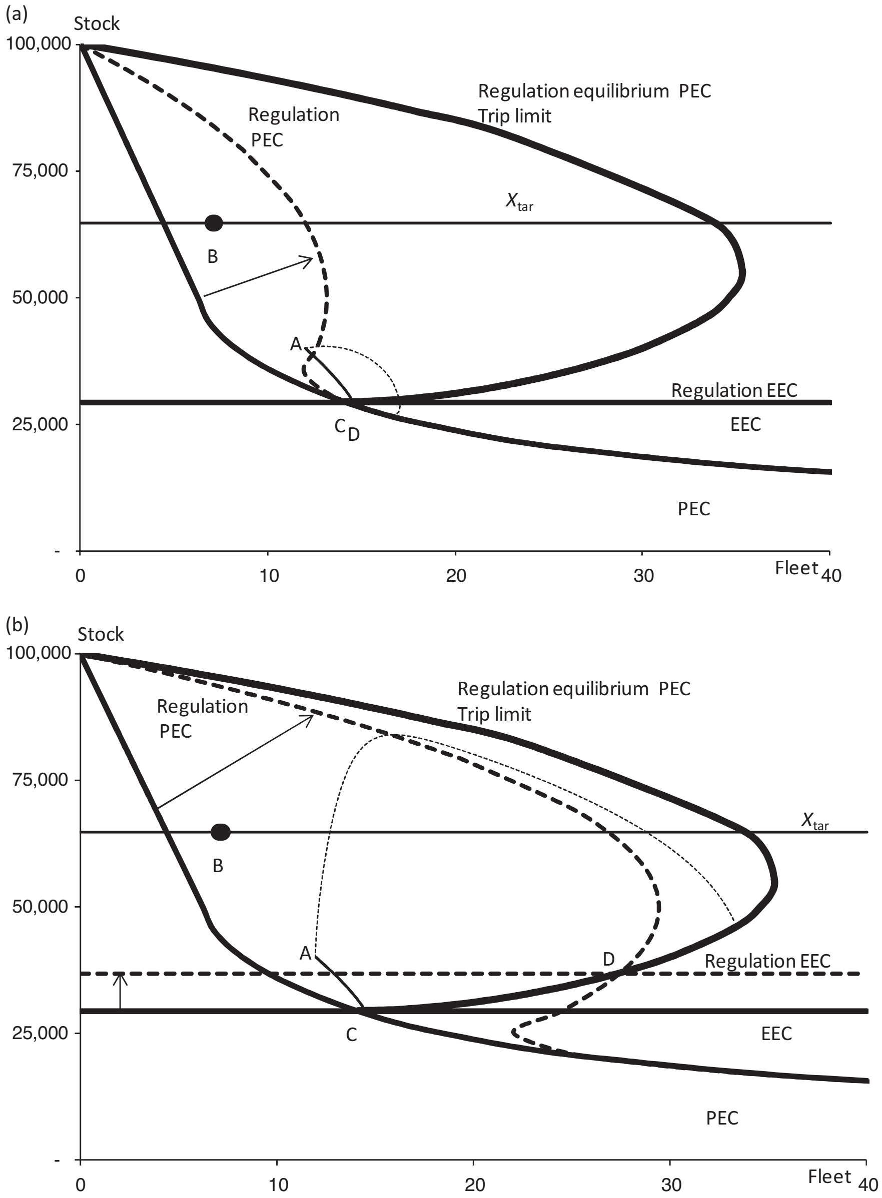

Figure 7.8 (a) Change in PEC, EEC, and trajectory for trip limits. (b) Change in PEC, EEC, and trajectory for trip limits II.

to the left of the status quo X_{BE} that the TL will change the bioeconomic equilibrium because it is only then that it will be a binding constraint.

Let us look at how the implementation of trip limits will affect the PEC and the EEC (see Figure 7.8a). Over the range of stock sizes where a trip limit imposes a binding constraint, $f_{tl}(X)$ must be substituted for $f^*(X)$ in the PEC equation, and as a result it will shift to the right. It will take more vessels to take the sustainable yield from each stock size. Over the range of stock sizes where the constraint is nonbinding, there will be no change in the PEC.

The EEC is mathematically complex in this case because there is no simple way to solve for the economic equilibrium stock size. However, it can be obtained numerically using the following equation:

$$X - \frac{\left\{c_i + c_s f_{\mathrm{tl}}^{*}(X) + \frac{\mathrm{FC}}{\left[D_{\max} f_{\mathrm{tl}}^{*}(X)\right]}\right\}}{Pq} = 0 \tag{7.15}$$

We need to find the X that will generate a value of $C_E \frac{\left[D_{\max} f_{\mathrm{tl}}^{*}(X)\right]}{Pq}$ that is equal to itself (see Equation 3.17).

The regulated EEC and PEC for the trip limit that results from the application of the static specification for our case study are pictured in Figure 7.8a (see Table 7.3, which shows that the trip limit required is 3.8). The EEC does not change because the $f_{\mathrm{tl}}(X)$ curve for a trip limit of 3.8 intersects the $f^{*}(X)$ curve to the right of X_{BE}. The constraint is not binding. This means that $f_{\mathrm{tl}}^{*}(X)$ in Equation 7.15 will equal $f^{*}(X)$, in which case the solution is X_{BE}.

The PEC does change. It becomes concave to the vertical axis. As X decreases, the allowable level of f increases. Eventually, a point is reached where the increase in f is such that the number of vessels must be reduced in order to keep the level of aggregate effort at the level which will harvest the sustainable yield. In this particular case, it becomes coterminous with the standard PEC at a stock size higher than X_{BE}.

To see why this is so, consider Figure 7.7 again. The $f_{\mathrm{tl}}(X)$ curve here is for the catch per day that exists at open access. The catch limit under consideration is higher than this, and so the relevant $f_{\mathrm{tl}}(X)$ will shift up and the curves will intersect at a stock size higher than status quo X_{BE}. It is only over the range where $f_{\mathrm{tl}}(X)$ is less than $f^{*}(X)$ that there will be a change in the PEC.

The bottom line is that the static trip limit calculated using current conditions at the status quo stock and fleet size will have no long-term effect on the bioeconomic equilibrium of the fishery. It will affect the trajectory to the equilibrium, however, because the regulation will impose binding constraints over some of the relevant stock sizes. While this again demonstrates the problems that arise when static traditional controls are specified using status quo values, it does not really shed much light on the actual effects of trip limits. But consider Figure 7.8b, which shows the effects of a trip limit of 1.7. In this case, the regulation PEC will be above the standard PEC. Again, the PEC shifts to the right because over the range where given the trip limit, it takes more vessels to take the sustainable catch for that stock size. The two PECs are not coterminous until well below the open access equilibrium at C.

The regulated equilibrium in this case is at point D. However, the PEC intersects the EEC from below and as the trajectory curve demonstrates, this is not a stable equilibrium. That is, the trajectory will cycle around the intersection of the two curves but will not settle there. While we do not want to dwell on intricacies of stability at this level of discussion, this is a very interesting aspect of trip limit regulations. Note that as the trip limit is made even tighter, the EEC is shifted up. At some point, it will intersect the PEC from above and there will be a stable equilibrium.

As a sidelight, consider how this regulation affects vessel behavior. While trip limits will not affect the actual cost curves, as is the case with season closures, vessel owners may be prohibited from operating by the MR equals MC principle. At whatever stock size the fishery is operating, if the constraint is binding, vessels will be operating at less than $f^*(X)$, the profit-maximizing level, which means they will be prohibited from operating at the minimum point on the vessel average cost curve. There will be too many boats each operating at a output level that is too low.

7.3.2.2.2 TACs

Let us now turn to the analysis of TAC regulations. It is possible to do so in a manner that is analogous to the EEC and PEC analysis. It is necessary, however, to construct different curves because of the differences introduced with a regulation that controls output. In the discussion, it will be necessary to compare the differences in the two sets of equilibrium curves and for definitional purposes, we will refer to the standard curves and the TAC curves.

A TAC is implemented by shutting down the fishery when the allowable harvest has been taken. There is, therefore, an implicit seasonal closure with a TAC, which depends on the stock and fleet size and the level of the TAC.

$$D_{\mathrm{TAC}} = \frac{\mathrm{TAC}}{[Vqf^*(X)\,X]} \tag{7.16}$$

Our analysis takes place in (X, V) space. To make the analysis work, it is necessary to assume that the TAC program can be perfectly enforced such that fishing will always be stopped when the catch reaches the TAC level. Under this assumption, for a given TAC level, there will be a specific season length associated with each combination of V and X, according to Equation 7.16. If the TAC is changed, the season length associated with each combination will change. But for a given TAC program, as V increases, D_{TAC} will decrease. Therefore, at any stock size, an increase in fleet size indicated by a movement to the right will mean a decrease in the associated season length for the relevant combination of V and X. This fact will be useful in interpreting the graphs presented below.

Given the perfect enforcement assumption, it is possible to construct curves that will serve the same purpose as the PEC and the EEC. The PEC in this case depends on the nature of the TAC program. To start, we use a constant TAC equal to y_{tar} to allow for an easy comparison with the previous analysis. For completeness, however, we will introduce programs where the TAC depends upon stock size below.

The concept of a PEC is that it divides the (X, V) space into areas where the stock will rise or fall based on the difference between harvest and growth. With a perfectly enforced TAC, there will be a biological equilibrium at stock sizes where growth equals the TAC. The equation for the PEC for TAC programs, $\text{PEC}_{(\text{TAC})}$, is:

$$G(X) = \text{TAC} = y_{\text{tar}} \tag{7.17}$$

There will be two solutions to this equation with a constant TAC, and both will be biological equilibria. A graphical picture of the solution in our example is shown in Figure 7.1. The target catch line intersects the growth curve at two points, and each will be a biological equilibrium because the regulated catch will equal growth. Technically, if catch remains equal to the TAC, the biological equilibrium on the left side of the curve will not be stable. Small increases in stock size will cause growth to become greater than catch and the stock will grow. The reverse will happen for small decreases in stock size. A more realistic interpretation of the potential of this instability follows from the analysis we are about to develop which takes industry behavior into account. The two PECs for our example are pictured in Figure 7.9. With a binding TAC, the stock size will fall in the areas above $\text{PEC}_{1(\text{TAC})}$ and below $\text{PEC}_{2(\text{TAC})}$ because the TAC is greater than stock growth. It will increase in the area between the two curves because the reverse condition holds (see Figure 7.1 again). If there is a change in the level of the TAC, the PECs will change.

The EEC divides the (V, X) space into areas where the fleet size will increase or decrease. With the standard curves, it is the stock size at which vessels are just covering all of their costs. Although not specified as such before, it is the stock size at which vessels will break even if they fish all available days. With TACs, however, the number of days that fishing is permitted will vary and this must be taken into account to derive the TAC equivalent of the EEC. The allowable

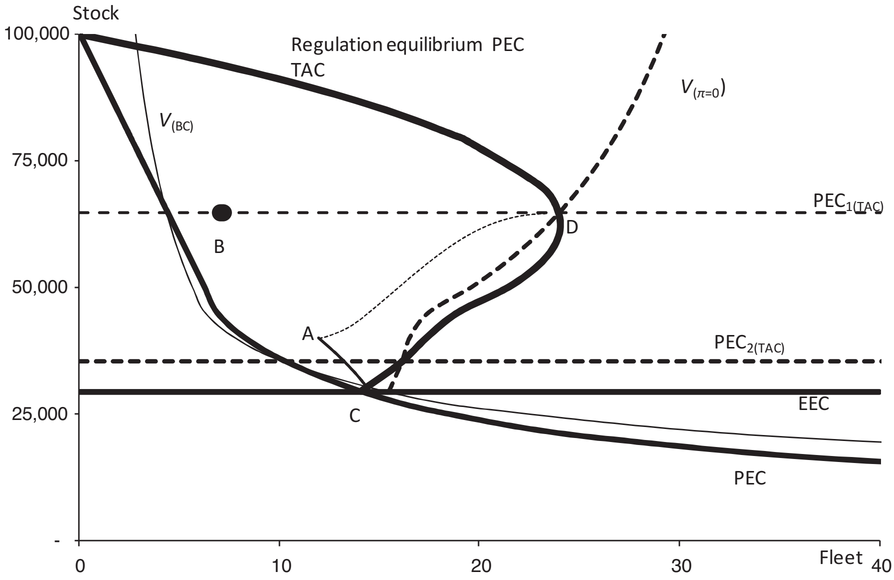

Figure 7.9 Change in PEC, EEC, and trajectory for a TAC.

number of fishing days is a critical determinate of the vessel profits. The vessel profit equation is:

$$\prod\nolimits_V = D\left[PqXf^*(X) - c_i f^*(X) - c_s f^*(X)^2\right] - \mathrm{FC} \tag{7.18}$$

The term in the [] parentheses is profit per day, π_D, which is a function of stock size and $f^*(X)$. Setting Equation 7.18 equal to zero and solving for $D(X)$ obtains:

$$D(X) = \frac{\mathrm{FC}}{[\pi_{\mathrm{D}}(X)]} \tag{7.19}$$

$D(X)$ is the number of days that a boat must fish at a given stock size in order to cover all costs. We know from the open access analysis that $D(X_{\mathrm{BE}}) = D_{\max}$. It follows that $D(X)$ will monotonically decrease from $D_{\max}$ as X increases from X_{BE}.

Using Equation 7.19, it is possible to derive the curve that is equivalent to the EEC under a TAC program when stock size is greater than X_{BE}. $D(X)$ is the minimum number of days a vessel can operate and still cover all costs. Therefore, given a specified TAC, the number of vessels operating at the breakeven point it takes to harvest the allowable catch at any given stock size is:

$$V_{(\prod=0)} = \frac{\mathrm{TAC}}{[D(X)\, f^*(X)\, qX]} \tag{7.20}$$

Put another way, this relationship shows, for a given TAC, the maximum number of vessels that can operate at any stock size above X_{BE} and just covers costs. It is the equivalent of the EEC for a TAC program.

To complete the interpretation of the various parts of (X, V) space, it is necessary to consider the possibility of nonbinding TACs. There will be cases where the fleet and stock combination at a given point will be such that the profit-maximizing behavior of the vessels will result in a harvest that is less than the TAC. The number of full-time vessels that can be supported by a given TAC can be expressed as:

$$V_{(\mathrm{BC})} = \frac{\mathrm{TAC}}{[D_{\max} f^*(X)\, qX]} \tag{7.21}$$

$V_{(\mathrm{BC})}$ will decrease as X increases. The notation (BC) stands for binding constraint. Points to the left of the curve represent X and V combinations where the TAC will not be a binding constraint because the fleet will not take the TAC even if it operates at full capacity.

The $V_{(\Pi=0)}$ and the $V_{(\mathrm{BC})}$ curves are both plotted in Figure 7.9. They will always intersect on the standard EEC curve at the point where the associated D_{TAC} will equal $D_{\max}$. The $V_{(\Pi=0)}$ curve is not defined for points below the standard EEC because profit is always negative for these combinations of X and

V. It will have a positive slope. At points to the right of the $V_{(\Pi=0)}$ curve, the fleet size will be such that vessels will be suffering losses due to the restricted season length, and fleet size will be decreasing in this portion of the graph. On the other hand, in the section to the left of the curve, profits will be positive and the fleet size will be increasing.

For a constant TAC, the $V_{(BC)}$ curve will have a negative slope. It intersects the standard PEC on both the $\mathrm{PEC}_{1(\mathrm{TAC})}$ and the $\mathrm{PEC}_{2(\mathrm{TAC})}$ because of the common equality of $G(X)$ and the TAC at those stock sizes.

The existence of an area where the TAC is not binding will affect the way that stock size will change in areas to the left of the standard PEC and above the $\mathrm{PEC}_{1(\mathrm{TAC})}$ and below the $\mathrm{PEC}_{2(\mathrm{TAC})}$. At stock sizes above the $\mathrm{PEC}_{1(\mathrm{TAC})}$, the stock size will fall with a binding constraint because harvest will be more than stock growth. However, with a nonbinding TAC, the stock size will change according to the standard PEC. Since the standard PEC lies to the left of the $V_{(BC)}$ curve, those points above $\mathrm{PEC}_{1(\mathrm{TAC})}$ represent X and V combinations where the TAC constraint is not binding and stock size will fall in the sub-area to the left of the standard PEC.

At stock sizes below $\mathrm{PEC}_{2(\mathrm{TAC})}$ with a binding TAC, stock size will fall because the TAC will be greater than growth. However, again the standard PEC lies to the left of the $V_{(BC)}$ curve in this area. As a result, the TAC will not be binding. Therefore, at points to the left of the standard PEC in this region, catch will be less than growth and stock size will increase.

In the region between the $\mathrm{PEC}_{1(\mathrm{TAC})}$ and the $\mathrm{PEC}_{2(\mathrm{TAC})}$, stock size will be growing because catch is less than growth. This stock size change conclusion will not change in the area where the TAC is not binding because that will only reduce the catch, and so stock size will still grow.

These differences in how stock size will change will have subtle, but sometimes important, effects on the regulated trajectory (see below).

Returning to the main analysis, note how the trajectory from the status quo point at A is changed as a result of the TAC program. On the dotted regulation trajectory, stock and fleet size will increase until an equilibrium is achieved at the intersection of the $\mathrm{PEC}_{1(\mathrm{TAC})}$ and the $V_{(\Pi=0)}$ curve. The reason for the difference in the open access and the TAC trajectories is that D adjusts according to Equation 7.16 such that the target harvest is always maintained. Total harvest will be less than growth until the stock grows to the target level.

A dynamic that is not pictured in the figure is how D changes over time. However, as explained above, as long as the TAC is maintained, movements to the right in (X, V) space generally mean that the season length is falling. The time path of D is shown in Figure 7.10. At the status quo point, when the TAC is initiated, the season is reduced to about 100 days. This is less than $D(X)$ for this stock size, and so profit is positive and the fleet size will increase. With a higher stock and fleet size, D will have to be reduced further in the next period in order to maintain the TAC. The fleet will continue to grow but the individual vessels will be working fewer days until eventually a bioeconomic equilibrium is reached. The TAC will be biologically effective because the target stock size will be achieved. The reason that it is effective is that, as opposed to the static input

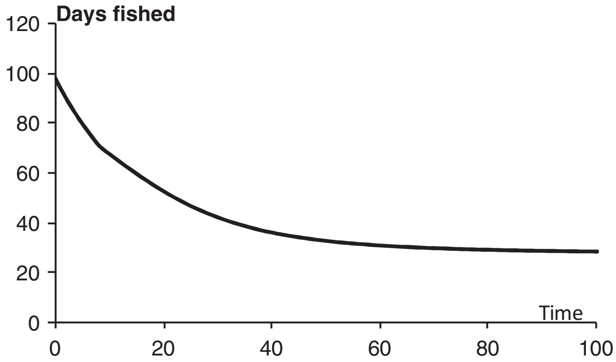

Figure 7.10 The effect of a TAC on season length over time.

controls, there is an endogenous change that corrects for the change in stock and fleet size. D changes automatically in a perfectly enforced system. Note that the TAC program is anything but effective from an economic standpoint. The equilibrium occurs with a large fleet and a short season.

To conclude this discussion, consider the case where, with a constant TAC, the status quo point is below the $\mathrm{PEC}_{2(\mathrm{TAC})}$. A strict biological interpretation of Figure 7.1 is that the stock will fall to zero because the TAC is greater than growth in that range of stock sizes. However, this misses the point that the TAC is a constraint on harvest. It is not a mandated harvest. Recall that to the left and below the $V_{(\mathrm{BC})}$ curve, the TAC is not a binding constraint and the dynamics of the fishery are the same as in the open access case. Note that at point C, the open access bioeconomic equilibrium lies in this part of the graph. Therefore, when the trajectory passes into this region, which it will if the status quo point is below the $\mathrm{PEC}_{2(\mathrm{TAC})}$, it will then proceed to the standard open access equilibrium. In summary, if the TAC is not binding, there will be no change in the bioeconomic equilibrium (see the exercises given in the CD).

For purposes of generality and also to set the discussion in a way that is analogous to stock rebuilding programs (see Chapter 6), let us analyze a more general type of TAC program where the permitted catch is not a constant but is related to stock size. Such a program can be described using Figure 7.11. A TAC function is graphed against the standard growth curve. The formula for the TAC(X) is:

$$\begin{array}{ll} \mathrm{TAC}(X) = -m + nX_t & \text{if TAC} > 0 \\ \mathrm{TAC} = 0 & \text{otherwise} \end{array} \tag{7.22}$$

If m and n are positive parameters, the curve will have a negative intercept and will cross the horizontal axis at a stock size equal to m/n. This would be the limit stock size below which harvest is not allowed. If m is set equal to zero, the target yield line becomes a constant fishing mortality curve. The limit stock size concept could be introduced in that case by specifying that the TAC formula does not apply for stock sizes below a critical level and the TAC is zero. The equilibrium stock size occurs where the TAC line intersects the growth curve.

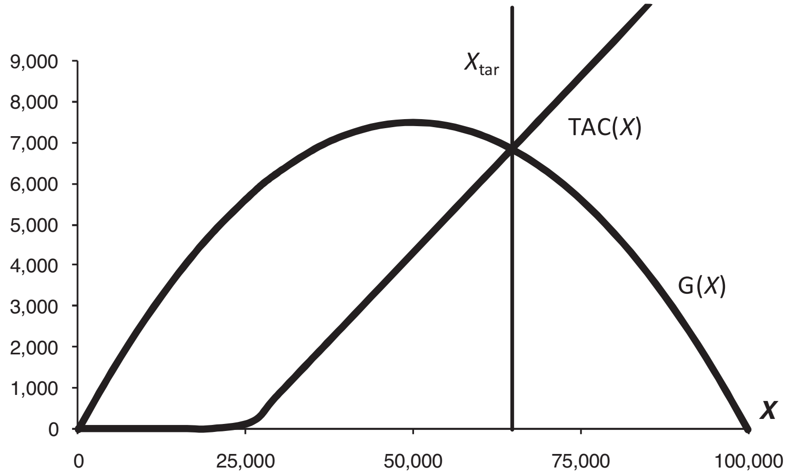

Figure 7.11 TAC as a function of stock size.

For comparative purposes, the TAC function in Figure 7.11 has been specified such that the equilibrium stock size is the same as the higher equilibrium, with the constant TAC function shown in Figure 7.1.

The comparison of status quo and the regulated open access for this TAC program is pictured in Figure 7.12. The main difference is that there is only one PEC$_{(\mathrm{TAC})}$, and there is no problem with a potential unstable equilibrium. The $V_{(\mathrm{BC})}$ and the $V_{(\Pi=0)}$ curves are still relevant, although they will originate further to the left on the standard EEC because the TAC is lower at lower stock sizes. For the same reason, the $V_{(\mathrm{BC})}$ will now have a positive slope.

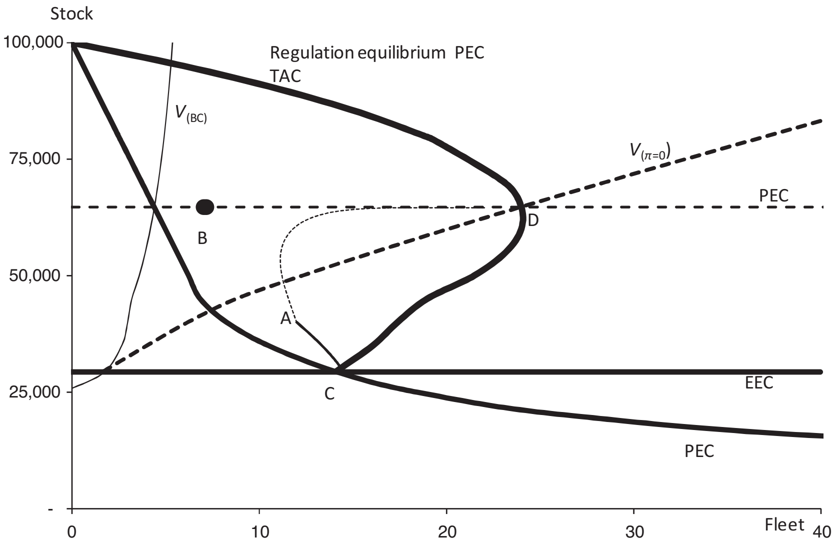

Figure 7.12 Change in PEC, EEC, and trajectory for a variable TAC.

The regulation trajectory has a somewhat different shape, however. Initially, the fleet size decreases because of the larger initial reduction of allowable harvest. However, as the stock and the TAC increase, the fleet size will increase as in the previous case. As before, when the fleet size is increasing the season length is decreasing. This is the endogenous change that keeps the regulation program on track in a biological sense.

7.3.3 Lessons learned

Let us take a moment and summarize the result thus far. Input controls and trip limits that are determined using the static specification equations will not be biologically successful because of endogenous changes in other variables in the system. The most important is that as stock size increases because of the initial success of the regulations, harvest will increase. The biological success of the program adds to its partial undoing. In addition, whatever biological gains are made (and they will be different depending on which particular control is used), come at the expense of inefficiency in harvest. The new PEC will be to the right of the standard PEC which means that it takes more vessels than are necessary to take the sustainable harvest at any stock size. However, a TAC program can be biologically successful if it is properly enforced because the endogenous change in the season length corrects for the other changes in the system. The target harvest will be achieved each period and this will eventually lead to the achievement of the target stock size. However, even with its biological success, there is an analogous problem with inefficiency. Input controls increase the cost of catching fish which causes an increase in the biological equilibrium. TACs will lead to a higher stock size, but an economic equilibrium can be achieved only when the increased profitability of the higher stock has been eaten up by larger fleets.

It is interesting to note that the above conclusions really only tell a part of the story because our model does not consider technological change. The process of innovation is ongoing under any circumstances. Regulations can be another incentive to be more innovative so as to circumvent the restrictions placed on productivity. To the extent that this is possible, the prospect for long-term biological gains will be reduced. In addition, however, the innovation process has been altered because instead of trying to lower costs on a wide open playing field, the game is changed. The object is to try to lower costs taking into account the regulated restrictions on production activity. This can lead to perverse results. A common example is that regulations on boat length can lead naval architects to come up with vessels that are much wider than would otherwise be considered.

7.3.4 Sequential regulation

The above discussion about the inability of traditional static fisheries regulations, other than enforceable TACs, to achieve biological goals and their weaknesses with respect to economic efficiency, provides a good framework for understanding the problems of modern-day fisheries regulations. However, it is only as good as far as it goes. Regulation agencies have the ability to change the level of restrictions implemented under particular regulation programs. For example, if a 9-month fishing season does not appear to be as effective in the third year as it was in the first year, regulators can cut the open season down to 8 months. Following Homans and Wilen (1997) and Anderson (2000), these sequential changes can be formalized by changing the specification equations after the first year as follows:

$$D_{r(t+1)} = \left[\frac{y_{\text{tar}}}{y_t}\right] D_t \tag{7.4a}$$

$$f_{r(t+1)} = \left[\frac{y_{\text{tar}}}{y_t}\right] f_{r(t)} \tag{7.5a}$$

$$q_{r(t+1)} = \left[\frac{y_{\text{tar}}}{y_t}\right] q_{r(t)} \tag{7.6a}$$

In terms of Equation 7.4a, the ratio of y_{tar} to current catch is used to adjust the season length for the next year. If current catch is equal to target catch, then no adjustment is necessary. However, if current catch is higher than the target (due to the weaknesses of static controls discussed above), then the season length needs to be reduced. Current catch carries implicit information on current stock and fleet size which are the two determinates of current harvests that are not subject to regulation with season controls. As they change, it is necessary to change the season length, which is exactly what the sequential specification equations do.

These sequential specification equations work regardless of whether y_{tar} is a constant or a function of (estimated) stock size, as in Figure 7.11.

The interpretation of the sequential specification Equations 7.5a and 7.6a is analogous. The sequential specification for trip limits is a little more tenuous because it does not take into account as much information (see Equation 7.7). It depends only on changes in fleet size.

$$\text{TL}_{(t+1)} = \frac{V_{\text{tar}}}{\left[D_{\max\ V_t}\right]} \tag{7.7a}$$

The revised specification equations provide a much more complete and informative way of looking at the management process. Managers do not implement regulations, and then stand idly by and watch the process unfold. They make adjustments. In this specification, we will assume that they make continuous adjustments in the regulation, but they could also make periodic changes in response to predetermined benchmarks of success or failure. We will continue the assumption that y_{tar} can be a constant or a function of X, and the terms y_{tar} and TAC will be used interchangeably.

Sequential regulation can be easily introduced into our simulation model. In addition to the changes in stock and fleet size, as demonstrated in Equations 3.26 and 3.27, the regulation is being changed through time. Let us consider the case of sequential season regulation as an example. Equation 7.4a becomes a third equation of motion for the system, and it will depend on whether the TAC for setting y_{tar} is a constant or a function of stock size. The season length becomes the third endogenous variable. An equilibrium will be achieved when $X_{t+1} = X_t$, $V_{t+1} = V_t$ and $D_{r(t+1)} = D_{r(t)}$ simultaneously.

We will have to modify the interpretation of the PEC and the EEC again in this case. As is the case in TAC programs, the PEC is replaced by a horizontal line at the target stock size(s). The concept of the EEC is not relevant under sequential regulation programs because some of the variables that define the EEC are changing overtime. The equilibrium will be achieved when the changes in fleet and stock size, as well as the regulation specification, cease.

Theoretically, sequential regulations have the potential to replicate the biological success of perfectly enforced TACs because they also make corrective changes to the regulated variable in response to the other variables as they change over time. In a TAC program, the fishery is shut down when the allowable harvest is taken, and the time allowed for fishing gets shorter as the stock size grows. This change in the open season is automatic and happens in real time. The sequential management of season length also makes adjustments to the allowable period for fishing, but there is a lag because the best that can be done is to set next year's season based on measurements of this year's stock, fleet, and catch which are subject to error.

In the context of our model, the trajectory curve of a sequentially determined season length program is analogous to that of a TAC program (see Figure 7.9 for the constant TAC case and Figure 7.12 for the variable TAC case). As specified in Equation 7.4a, the only difference is the time lag. Both trajectories are based on the same target stock size, and while they may take a slightly different path from the status quo position, they will end up at the same equilibrium point. Further, the equilibrium season length will be the same in both situations.

Using sequential adjustments for the other regulation types leads to similar results. The trajectories for sequential f, q, and trip limits look very similar to those for TACs. There are some interesting sidelights on stability, however. These issues will be discussed in the exercises given in the CD. The equilibrium values of the variables with the different sequential regulation programs are shown in rows 10–13 in Table 7.3. Note that all of them will achieve an equilibrium at X_{tar}. Note also how the regulation level is changed over the sequential process. For example, the static regulation level of D was 98, which did not achieve X_{tar}. However, over time, it was reduced to 28 and the target stock size was achieved.

Note that if the season length was reduced to 28 days from the start, the program would cause the fishery to eventually reach a regulated equilibrium at X_{tar}. However, there is no simple specification equation to determine that from the start. That is why the sequential process is necessary. Granted, using the information contained in our model, it is possible to solve for the season length to achieve X_{tar}, but that sort of information is not typically available to fisheries agencies.

Also note that the equilibrium values for trip limits are the same as those for f restrictions because one is the flip side of the other. The sequential regulation will reach an equilibrium when the trip limit is equal to 1.35, and at that point the equilibrium value of f will be 0.42. At the same time, the sequential regulation of f will achieve an equilibrium when the daily effort is restricted to 0.42. At that point, the catch per day will be 1.35. Similarly, a sequential seasonal control program will reach an equilibrium when the allowable number of fishing days is 28 and the catch at that point is equal to y_{tar}.

It should be noted that the theoretical similarity of the trajectory curves for perfectly enforced TACs and sequential regulation programs rests on some strong assumptions. Both trajectories are based on the assumption of perfect enforcement, but the sequential management assumption depends on the availability and accuracy of reported data and the political will to stick to the course. The point is that gloomy views provided by analyzing the effects of static regulations are likely to be overly pessimistic. Sequential regulations have the *potential* to correct for the problems of static regulations such that biological goals can be achieved. However, it is not as potentially reliable as a TAC program.

7.3.5 The relationship between regulation programs and fleet capacity

The main conclusions so far can be summarized as follows: Except for TACs, static regulations will not be successful in achieving biological goals. Perfectly enforced TACs can achieve them, and sequential regulation programs have the potential to do so. So, is this the end of the story? From a purely biological point of view, and ignoring the effects of uncertainty and political influences in regulation, it might be. But this is a bioeconomic analysis of fisheries management and regulation.

Let us set the stage for the discussion of limited-access programs by turning the focus on the economic efficiency aspects of different types of regulation. This can be done by introducing the concept of a regulation equilibrium PEC. To start this at the beginning, consider Figure 7.4 again, which was the first in our series of graphs explaining the effects of the various regulations. One conclusion was that the specified reduction in season length would change the bioeconomic equilibrium from the unregulated situation at point C to the regulated equilibrium at point D. Other season lengths would result in different regulated equilibrium points. Put in other words, this means that, theoretically, any stock size can be achieved by a regulation program that controls season length. It is just a matter of finding the right season length. The same can be said for other types of regulations such as trip limits. We will define the regulation equilibrium PEC as the collection of bioeconomic equilibrium points in (X, V) space for a particular type of regulation. The regulation equilibrium PEC is also shown in Figure 7.4. It shows the equilibrium fleet size and stock combination as the season length is reduced from D_{max} (no regulation) to zero (shutting down the fishery). Note

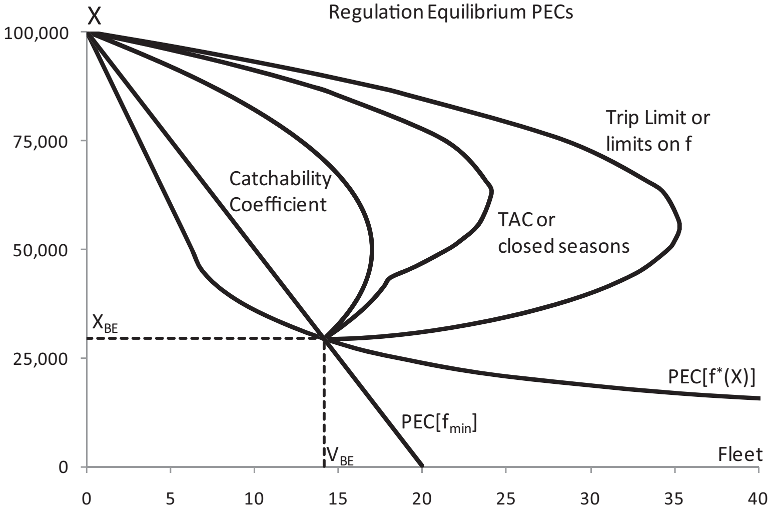

Figure 7.13 Regulation equilibrium PECs for different types of regulations.

that it does go through point D, the equilibrium point under consideration in the figure. The relevant regulation equilibrium PECs for the other regulation programs have been pictured in Figures 7.5, 7.6, 7.8a, 7.8b, 7.9, and 7.12. The derivation of these curves is explained in the exercises to this chapter.

These regulation equilibrium PECs are shown together in Figure 7.13. There are only three because the curve for TACs is the same as the one for season control, and the one for trip limits is the same as the one for regulations on daily effort for reasons that have been explained above. Two other curves are included for comparison purposes. The standard open access PEC is the curve labeled PEC[$f^*(x)$]. For the purposes of comparison here, we have added the extra notation as a reminder that this PEC shows the number of vessels necessary to take the sustainable yield from the given stock size if the boats operated at $f^*(X)$, the profit-maximizing level of output for that stock size. The curve labeled PEC[$f_{\min}$] shows the number of boats necessary to take the sustainable yield when vessels operate at $f_{\min}$, the level of daily effort that causes the boat to operate at the minimum of the average cost curve. In contrast to the regulation equilibrium PECs, which show the fleet size that will be achieved at a given stock size for a given regulation, the PEC[$f_{\min}$] shows the fleet size that will take the sustainable harvest from any stock size at the lowest possible cost. Both the PEC[$f_{\min}$] and the PEC[$f^*(X)$] curves go through the open access equilibrium point, because at that point the boats are operated where $f^*(X)$ equals $f_{\min}$.

Note that PEC[$f_{\min}$] lies to the right of the PEC[$f^*(X)$]. If vessels are maximizing individual profits for the given stock size on the PEC[$f^*(X)$], why does the PEC[$f_{\min}$] show the most efficient fleet size for the sustainable yield at that stock size? The answer is that individual vessel profits are not the main concern when looking for overall fleet efficiency. The idea is to take the sustainable harvest at the lowest possible cost. The horizontal difference between the two curves is explained by the fact that at any stock size, a larger fleet each operating at $f_{\min}$ will have a lower total cost than the smaller fleet each operating at $f^*(X)$ (see the discussion about the determination of the optimal combination of fleet size and vessel operation to obtain a static MEY around Equations 3.20–3.22).

Now consider the trio of regulation equilibrium PECs. The relevant range for stock size is from the open access equilibrium level, X_{BE} up to K, the virgin stock size. In each case, the curves are concave to the vertical axis, although it is important to remember that the shapes of the curves and, more importantly, the relative differences between them depend on the specific parameters used and the results are not necessarily general.

However, according to these curves, at first there is a positive relationship between equilibrium stock size achieved and the regulated fleet size. This makes intuitive sense and is related to two things. First, as the stock is increased toward X_{MSY}, the sustainable yield will be increased. Second, because of the inefficiencies caused by the regulations, more vessels will be needed to take any catch level. Eventually, however, as the sustainable catch falls at higher stock sizes, the regulated equilibrium fleet size associated with regulated equilibrium stock size will fall.

Note, however, that the regulation equilibrium PECs do not reach a maximum fleet size at X_{MSY} where sustainable harvest is maximized. At each stock size, the regulated fleet size is the one that will cause vessel profits to fall to zero. In other words, the size of the regulated equilibrium fleet that can be sustained at any stock size depends on the amount of potential profit and how the vessel cost structure is affected by the regulations. It appears that the maximum fleet size for a TAC is close to X_{MEY}, the stock size that generates the maximum sustainable profit.

The interpretation of the horizontal differences between these curves can be very illuminating. In the first place, the differences between the set of regulation equilibrium PECs demonstrate that different regulations can have different effects on fleet size. In our case, it appears that trip limits will cause the largest increases in fleet size, but these results cannot be generalized to all cases. The point is that different effects are possible.

The horizontal differences between a particular regulation equilibrium PEC and the PEC[$f_{\min}$] is an indication of the inefficiency effects. At any stock size, every regulation type will produce a fleet that is larger than is necessary to produce the sustainable yield at the lowest possible cost. Just as important, in most cases, the individual boats in the fleet will be operating inefficiently in that they will not be minimizing costs for their given vessel level of output.

There is an interesting twist here, however. When traditional open access measures are used to increase the equilibrium stock size, the resultant fleet size will be larger than the efficient one. However, if unregulated vessels were allowed to operate at that stock size, their output would be such that a fleet smaller than the efficient one would be able to take the sustainable harvest.

The discussion in the previous sections has already demonstrated that the only way that traditional open access regulations can increase equilibrium stock size is to increase the cost of fishing. This analysis adds a little more to that conclusion.

While open access regulations can increase the equilibrium stock size, they will also affect fleet size and the way in which the fleets operate. For the most part, it is likely that over-the-relevant-range programs that increase stock size will also indirectly increase fleet size. More to the point, the fleet sizes will be larger than necessary to take the sustainable harvest. In many cases, not only will there be too many boats, individually they will be operating inefficiently, in the sense that they could produce their output at a lower per unit cost.

Further, the comparative analysis shows that the choice of regulation type will determine how the fleet size is affected. While all programs can theoretically achieve a desired stock size, they will have different effects on fleet size and vessel operation.

Other implications of these results are worth noting. The number of participants can have a significant impact on the everyday operation of a regulated fishery. For one thing, the more participants there are, the more difficult and expensive it can be to monitor their behavior and obtain compliance. In addition, more participants can increase the political difficulties that often prevent the appropriate management steps from being followed (see the previous chapter).

It is also important to keep in mind that once these boats are built, they do not go away. They will be around for the length of a normal boat life. Overcapacity, which is a condition where the existing fleet is larger than is necessary to take the desired harvest, can result from the open access overlap that results as the fishery moves along its trajectory toward an equilibrium (see above), but it is important to remember that it can also be the (unintended) result of management programs. Either way, the process of moving to a more rationalized management scheme is made all the more difficult the more participants there are.

7.4 Limited-access regulation

We now turn to a discussion of limited-access regulations. We continue to follow the semihistorical prospective and introduce limited-license programs first. They are the input side of limited-access regulations. We then turn to ITQs which are the output-based limited-access regulations.

In the initial chapters of this book, we demonstrated that open access utilization of a fishery (no restrictions on the number of participants or on their activities) will lead to biological and economic problems. The discussion of open access regulations in the first part of this chapter has shown that serious problems can continue even under regulation. Well-intentioned programs can fail to achieve biological targets, but even when they are successful, open access regulations directly or indirectly cause the fleet size to grow larger than necessary. A logical next step would be to place a limit on the number of participants. While this may be logical in the context of the above discussion, until relatively recently, it has not been actively considered because of the radical changes it would impose on the way a fishery would work. The first major license limitation program was introduced in the British Columbia salmon fishery in 1968 (see Morehouse, 1980). Over time in most western countries, people have enjoyed relatively free access to fishery resources, and for political and cultural reasons, the government has been hesitant to consider restricting access. But, as a result of the lack of success of regulated open access fisheries, it is now a viable option in most places, although it certainly does not meet with universal acceptance.

7.4.1 Limited-license programs

The discussion of limited-license programs can be quite succinct, given the previous analysis. We will first demonstrate the effects of the basic case where the limit on the number of participants is the sole form of control. We then consider the case where the limited number of participants is also subject to supplemental input or output restrictions. A side benefit of the analysis is a more in-depth discussion of the optimal way to produce fishing effort.

For simplicity in our theoretical discussion, we will assume that the limited licenses are issued to vessels, although some caveats to the results that follow are provided below. Without a license, a vessel cannot operate in the fishery. We start with a very simple geometric interpretation and then move on to a discussion of the nuances involved. As in our previous discussions, we need to show how the PEC and the EEC, or their operational equivalents, will change as a result of the regulation. Under open access, the equilibrium occurs at the intersection of the PEC and the EEC. A pure license-limitation program will have no effect on the PEC, but it will affect the area in (X, V) space where the EEC is operational. For continuity with the previous discussion, we assume that the limitation program has been established using Equation 7.3; that is, the number of vessels has been set so as to achieve the same short-run objective as the other static regulations. The vertical dotted line in Figure 7.14 represents the limited number of boats that are permitted under this program.

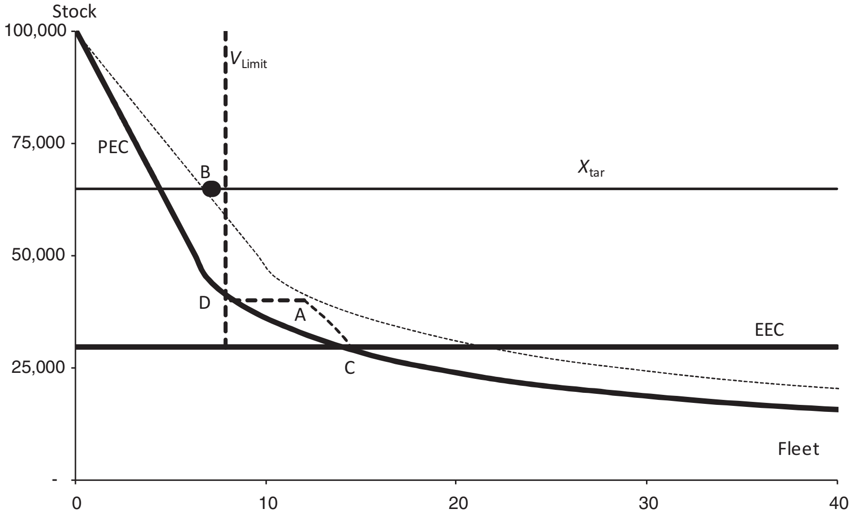

Figure 7.14 Change in PEC, EEC, and trajectory for a limited-license program.

Assuming, as usual, that our regulations can be enforced, then regardless of the level of vessel profits, the fleet cannot grow beyond V_{Limit}. The operational vessel equilibrium curve will be the EEC out to V_{Limit}, and it will be the vertical line at V_{Limit} after that. The regulated equilibrium will occur at the intersection of the PEC and the operational vessel equilibrium curve (see point D in Figure 7.14). The short-run effects are shown by the regulated trajectory emanating from the status quo point at point A. There will be an immediate drop in fleet size back to V_{Limit}. In this particular case, the immediate decrease in the fleet will put the fishery very close to the regulated equilibrium which occurs at the intersection of the V_{Limit} curve and the PEC. The values of the variables at this equilibrium point are shown in row 14 of Table 7.3. Like the other static regulations, a limit on vessels based on the necessary reduction in current catch will not be successful in achieving X_{tar}. However, because of the limit on entry, the main source of secondary expansion of effort is blocked, and there is an increase in the equilibrium stock size. Compare Points C and D.

An important conclusion is that to the extent that the license-limitation programs do impose a binding constraint on fleet size, they will result in an increase in the equilibrium stock size. The PEC is downward sloping. A binding V_{Limit} constraint will therefore intersect the PEC at a higher stock size. Further, the tighter the constraint, the larger will be the increase in equilibrium stock size.

It follows that a license-limitation program will have no long-run effect unless it places a binding constraint on fleet size. The vessel limit has to be less than the open access fleet size, or the regulated equilibrium fleet size, if there are other regulations in effect (see below). A limit beyond that size will protect against further expansion if prices, costs, or technology change, and it can affect the open access trajectory, but it will have no long-run effects.

It can be noted as an aside that because of political limitations, the number of licenses in real-world programs is often so large that there is not much constraint on fishing operations, except perhaps against further expansion. That, of course, is an issue of implementation, not a problem of the conceptual workings of such a program.

Not only will a limited-license program increase stock size, it will do so in a way that also allows for positive profits at the regulated equilibrium. This is because the entry of vessels is blocked by regulation; it is not stopped by the economic constraint of zero economic profits as it is under open access. As a result, all of the rents of the fishery will not be dissipated through open access entry. Note that the regulated equilibrium at point D is above the EEC, which means that vessel profits are positive. This is demonstrated in the final column of Table 7.2. The cost per fish is no longer pushed to our assumed price of \$17.00. The remaining vessels are earning profits. We will return to this in a little more detail below.

But let us put this into perspective. While license-limitation programs can increase stock size, by their very nature, they cannot be used as a primary tool to control it. The number of licenses is not something that can be changed sequentially in the same way that trip limits and season closures can. Further, just looking at the effects of changes in the V_{Limit} curve ignores the time it would take the trajectory to move to the new equilibrium.

One of the promised caveats is that our results depend on our assumption of fixed prices, costs, and especially technology. With the limited license program, the remaining fleet will have incentives to find ways to increase prices, lower cost, and improve technology. Changes in the first two will change only the amount of profits each will earn. However, improvements in technology will lower the PEC, which means that some of the biological gains will be lost. An interesting point is that the profits earned as a result of the limited entry provide both a spur and a source of financing for the market and technological improvements.

But the inability to make frequent changes in the number of licenses does not mean that nothing can be done to address necessary stock improvements. Traditional input and output controls can be added as supplemental regulations to a limited-license program. The analysis of the effects of doing so is straightforward. Recall that the result of implementing any of the input or output controls discussed above was that the PEC would shift upward and to the right. The regulated equilibrium stock size that will result from a license-limitation program with supplemental regulation will occur at the regulation PEC and the V_{Limit} curve. Supplemental regulations will lead to further increases in bioeconomic equilibrium stock size, depending on how far the regulation PEC shifts up along the V_{Limit} curve. For example, consider Figure 7.4, which shows the effects of a controlled season length of 98 days. The regulation PEC for this control is reproduced as the thin dotted downward sloping curve in Figure 7.14. If our license-limitation program were supplemented by a season control of 98 days, the regulated equilibrium stock would occur at the intersection of that curve and the V_{Limit} curve at point B.

In this light, consider the TAC program represented in Figure 7.12. The regulated equilibrium will occur at point D. However, a different regulated equilibrium could be obtained by introducing a limited license program that places a V_{Limit} curve anywhere to the left of that point. A new equilibrium will occur at the intersection of the V_{Limit} curve and the PEC. Because the PEC is horizontal, the supplemental regulation will not increase the stock size but it will have a beneficial effect on fleet expansion. Vessels will be earning profits because the new equilibrium will occur to the left of the $V_{(\pi=0)}$ curve. Other cases of license programs with supplemental regulations will be considered in the exercises given in the CD.

From the first example, we can conclude that adding supplemental regulations to license-limitation programs can cause further increases in stock size. But, in addition, the last example shows that adding limited-license programs to a TAC program, and by implication to any sequential regulation program, can prevent the full fleet expansion that would occur with open access. In the TAC case, the fleet will be smaller and the season length will be longer, but it will still be less than D_{max}, which means that there will still be economic inefficiencies.

Let us change the focus slightly and look in more detail at the economic aspects of these results. We have already established that the limit on vessel entry results in positive net revenues at the regulated bioeconomic equilibrium. But, while supplemental regulations can lead to further increases in equilibrium stock size, what effect will they have on the size of the net returns? The answer turns on the general solution of optimal utilization of a fishery, as described in Equations 3.19–3.21. It is more than determining the optimal amount of effort, it is necessary to simultaneously determine the optimal combination of fleet size and daily effort by which the optimal amount will be produced. The reason that an open access fishery will not produce that optimal combination is that the determinations of total fleet size and of the amount of daily effort are individual decisions based on different criteria than those used to determine the optimal amount of effort (see above).

A limited-license program can only go part of the way from open access utilization toward optimal utilization. The reduction from the open access fleet size will produce gains because of the reduction of effort. However, it will only by chance lead to the optimal fleet size. And for reasons described above, no matter what the fixed fleet size is, the individual owners will make decisions on daily effort based on private-maximizing criteria rather than joint profit-maximizing behavior which would consider the effects they are each having on the others through their effects on the stock.

Using our example as a case in point, at the regulated equilibrium, each vessel will be producing effort according to our $f^*(X)$ function. However, using Equation 3.21, it is possible to solve for a second best optimal level of daily effort, given the fleet size of V_{Limit} (see the exercises to this chapter). Generalizing this, we can conclude that, up to a point, adding supplemental controls on daily effort to a limited-license program with no other side controls can increase the equilibrium stock size and the net returns to individual operators. Other types of supplemental controls will also increase the equilibrium stock size and they may increase net returns as well. It depends on the net effect of the changes in stock size, sustainable yield, and the cost of producing effort. For example, season controls have different effects on the cost of producing effort than do controls on f (see Table 7.2) and, in addition, some of the reduction in effort due to the restriction on days fished will be lost because of the increase in daily f because of the increase in stock size.

One interesting policy suggestion follows from this theoretical discussion: the possibility of negotiating self-imposed supplemental regulations among the remaining permitted participants in the limited-license fishery. If their number is small, their actions are transparent to each other, and the vessel restriction is known to be enforced it may be possible for participants to mutually agree to cut back daily effort, knowing that the in the long run their individual returns will increase (see Ostrom *et al.*, 1994).

Buybacks are another type of effort control program that can be analyzed in the context of this discussion. As the name implies, *buybacks* reduce potential fleet effort by purchasing vessels from individual owners and retiring them from the fleet. Given space constraints, we cannot provide a detailed discussion here, but the interested reader is referred to the list of suggested readings at the end of the chapter.

Several summary statements, based on the above conclusions, are possible, however. First, without a license-limitation program, buybacks are a temporary solution at best. Second, if the fishery is on a trajectory where the fleet is already decreasing, there may be no need for a buyback. Normal exit will reduce the fleet to its equilibrium size. The buyback may speed up the exit and will also provide financial assistance to exiting participants. In general, however, a buyback will produce a sudden jump along the trajectory, but the fleet will resume the path to the equilibrium. There will be no long-term gain. In addition, a temporary change in fleet size is a very coarse means of control. It is very hard to set it so as to achieve a target stock size. In addition, it is a very elastic constraint because remaining vessels will increase production of effort with increases in stock size and can also do so independent of stock size by changing technology.

This analysis shows that limited-license programs can be a very important component of modern-day fisheries management regimes. They can significantly improve results of traditional management. They offer the potential to increase the equilibrium stock size and to allow for positive net returns. They can correct for some of the dissipation problems of open access. There are some important caveats, however, that need to be considered when implementing them. While they do not point out fatal flaws, they indicate important things that should be considered when implementing these programs.

First, it is critical to keep in mind that the beneficial results are dependent on the assumptions that underlie the models. The models have to take the status quo level of technology as a given. And yet over time, technology will change. And more directly to the point, because this is an input-based program, there is a tendency for technology to change such that the input restrictions become less binding. In terms of the model, this means that the upward shifts in the PECs that result from supplemental regulations will likely be followed by downward shifts due to technological change. The gains in terms of stock size and economic returns may be transitory.

Second, the model assumes a homogeneous fleet and that licenses can be assigned to individual vessels. In reality, of course, there are many different types of boats and each will frequently, but independently, undergo upgrades based on technological improvements. In some cases, it may be more appropriate to license units of gear such as fish traps. In either case, it is difficult to come up with an appropriate measure of effort. A 100-m vessel is not that same as a 200-m vessel; nor are two 100-m vessels likely to be equivalent to one 200-m vessel. There can be difficulties when there is a need to transfer a license from one boat to another or a boat needs to be replaced. The real problem is how the amount of fishing power within the limited-license program can be limited to a fixed amount over time. For more detail on the practical problems involved, see Suggested Readings.

A final caveat follows from the discussion of the optimal production of effort under these programs. While the concepts are correct, it would be a leap of faith to take the argument to its logical extreme and think that a limit on vessels could be followed by a limit on effort per day, and then with other sorts of controls to finally arrive at a proper sized fleet operating in the appropriate manner. But this is a very nice segue to our discussion of ITQs. Because of the differences in the nature of the permit to participate, the incentives of the participants are such that there will be a tendency for the TAC to be produced as efficiently as possible such that the economic returns are maximized.

7.4.2 Limited access permits

7.4.2.1 Introduction

Let us now turn to a discussion of limited access permits (LAPs). As noted above, this is a more recent name for what were initially called individual transferable quotas (ITQs). The purpose will be to show how the change from a permit system based on inputs to one based on outputs will provide a better basis for achieving biological goals and at the same time will produce incentives for optimal fleet operation.

The bottom line of this analysis is that a properly designed and functioning LAP program will provide incentives such that the target catch will be achieved each period and the cost of harvesting the TAC will be minimized. The process by which this is accomplished is somewhat complex and the description of how it works can become quite convoluted. It will prove useful to present a concise statement of the parts of the process and then to return to describe the details of each part and to conclude with a general summary.

The permit to harvest is the core of a LAP program. It becomes a proxy that can address problems caused by the lack of individual ownership. The permits become valuable assets which will have a market price determined by their relative scarcity. Participants will undertake profit-maximizing behavior but with the important difference that they will make decisions for the joint utilization of their vessels and their use or acquisition of the necessary permits. With a given TAC and a functioning enforcement program, the workings of the permit market will cause the individual vessel profit-maximizing levels of effort produced at any combination of stock and fleet size to simultaneously coincide with the level necessary to take the TAC and to minimize the total fleet-wide cost of doing so. The resulting rents from this efficient production will accrue to the owners of the permits, while vessel owners will earn a normal return. The workings of the permit market prevent the rent dissipation which occurs under open access. These results will occur regularly along the regulated fishery trajectory as the fleet, the stock, and the TAC (if it is a function of stock size) change over time. At the regulated bioeconomic equilibrium, the TAC program and the workings of the permit market will have produced a catch that is equal to the growth of the target stock size and will have generated the optimal fleet size which will operate in the most efficient way to harvest that catch.

The explanation of this process will require discussions on the design of the LAP program, the workings of the permit market, the static profit-maximizing behavior of participants, and the dynamic fishery wide effects. Each will be discussed below.

7.4.2.2 Description of LAP programs

For purposes here, we will describe the elements that will be necessary for a functioning LAP program to achieve the above results. In the real world, there are many ways to design an actual LAP program, depending on the nature of the fishery and on the specific goals it is designed to achieve (see the summary discussion and the Suggested Readings provided below).

The biological component of a LAP program is a TAC, where the permitted annual catch is a fixed amount or specified as a function of stock size. As with a regular TAC program, it must be possible to enforce the TAC. In this case, it is more than preventing actual harvest from exceeding the *total* allowable catch. It is also necessary to ensure that no vessel is able to land a unit of fish without the required permit. The enforcement ability is necessary for the biological success of the program, but it is also critical to the economics. If nonpermit holders can land fish, the value of the permits will be diminished and their market value will not produce the desired results.

It is also necessary that there is a direct relationship between the number of harvesting permits and the TAC. Also, there must be a way for the permissible harvest to change if the TAC is a function of stock size. This is most easily accomplished if the harvest permit system is broken into two levels. Let quota share (QS) refer to permits issued in terms of a percentage of the TAC. Each year, the QS will generate annual harvest permits, AHPs, measured in units of fish. If an entity has QS equal to 10% of the TAC, each year it will be issued permits to harvest equal to 10% of the TAC. It should be very clear that the QS permits are enduring. They will generate AHP for as long as the program remains in effect. On the other hand, AHPs are short-term annual permits to harvest. They are valid only for the year in which they are issued.

For the program to work as designed, both QS and AHP must be divisible and freely transferable. We will describe below how the market price of a unit of AHP is determined. The value of a unit of QS is the present value of the stream of AHP that it will generate. There is considerable uncertainty involved, not the least of which is that the physical amount of harvest allowed in any year can change, depending on stock conditions. The discussion here will focus on the market value for the annual permits to harvest, the AHPs. They are at the center of the workings of the system.

While the initial allocation of the QS permits is a critical policy issue with serious political and distribution effects, with transferability, it will have no effect on the final results (see Suggested Readings below for more details on the pros and cons of different types of initial allocation procedures).

7.4.2.3 Market for AHP

The basic workings of a LAP program can be analyzed by focusing on the transferability of AHP. It is important to remember that an AHP is a permit to harvest a certain amount of catch in a given year. If AHPs are transferable, AHP owners and boat owners can buy and sell them as they choose. Since production of fish is possible only if supported by an accompanying unit of AHP, we treat the control of a unit of AHP as synonymous with production. If an owner of AHP does not want to use the AHP, he or she can sell it. If an AHP program is to work, there must be a well-functioning market for permits that can generate an equilibrium annual trading price, call it, P^*_{AHP}. There are two questions at this point. First, in any given year, how is the equilibrium price of AHP determined? Second, how will the existing amount of AHP be allocated among the current fleet? The questions are related. In fact, they are answered simultaneously, but it is useful to consider them separately.

Consider the workings of the AHP market. Like any other price, P^*_{AHP} will be determined by the demand and supply curves for AHP, both of which can change through time as a result of changes in stock and fleet size. The supply curve is a vertical line equal to the TAC for the current year. If TAC is a function of the stock size, it will change over time with changes in stock size.

The demand curve for AHP is a derived demand because what people will be willing to pay for the right to harvest depends on the net return that can be earned from landing a unit of fish. How much will they receive for the fish when it is taken and how much will it cost to bring it to shore? The demand (or the marginal willingness to pay) for a unit of AHP is the price of fish minus the marginal cost of fish, MC(y).

In order to calculate MC(y), it is necessary to transform cost in terms of effort, which is how we have been measuring it thus far, into cost in terms of fish. Given the fleet size at any point in time, V_t, the total cost of producing aggregate effort ($E_t = V_t D_{\max} f_t$) is:

$$\text{Fleet} \quad TC(E_t) = TC(V_t,\ f_t)$$

$$TC(E_t) = V_t D_{\max}\left(c_i f_t + c_s f_t^2\right) + V_t FC \tag{7.23}$$

The short-run fleet production function is:

$$y_t = V_t D_{\max} f_t q X_t \tag{7.24}$$

Therefore, the level of daily effort per boat that will be necessary to take a given amount of catch for a given combination of X and V is:

$$f_t = \frac{y_t}{[V_t D_{\max} q X_t]} \tag{7.25}$$

Substituting Equation 7.25 into Equation 7.23 yields the equation for the fleet total cost of output. After some simplification, we have:

$$\text{Fleet} \qquad TC(y_t) = TC(y_t,\ V_t,\ X_t)$$

$$TC(y_t) = \frac{c_i y_t}{q X_t} + \frac{c_s y^2}{\left[V_t D_{\max} q^2 X_t^2\right]} + V_t FC \tag{7.26}$$

The cost of total landings will depend not only on the amount produced but also on the current stock and fleet size. It will increase with output, but for a given level of catch, it will decrease with stock size because of the resultant increase in the productivity of effort. The effect of an increase in fleet size at a given level of output is indeterminate. Effort per boat is lower for the same level of catch which will lower cost because there is an increasing marginal cost of effort per boat. At the same time, an increase in the fleet will increase fixed cost. Total cost depends on both the size of the fleet and how the fleet is operated.

Given the maximum amount of daily effort that a boat can produce, there is also a maximum amount of fish that can be produced, depending on the fleet size. The level of output in Equation 7.26 can never be higher than $V_t D_{\max} q X_t \max f$. This technicality is addressed in the derivations below (see Equation 7.31).

The annual demand curve for AHP can be expressed as:

$$P_{\mathrm{AHP}(t)} = P - \mathrm{MC}\,(y_t,\ X_t,\ V_t) \tag{7.27}$$

The function $\mathrm{MC}(y_t,\ X_t,\ V_t)$ is the first derivative of the total cost function Equation 7.26 as follows:

$$\mathrm{MC}\,(y_t,\ X_t,\ V_t) = \frac{c_i}{qX_t} + \frac{2c_s y_t}{\left[V_t D_{\max} q^2 X_t^2\right]} \tag{7.28}$$

The demand curve for AHP will shift to the right with an increase in fleet size, and vice versa. Therefore an increase in V will increase its price.

Under the assumption that the TAC is a function of stock size, an increase in stock size will shift both the demand and supply curves to the right. The effect of this on $P^*_{\mathrm{AHP}(t)}$ is indeterminate. The demand curve shift will increase price, but at the same time the supply curve shift will lower price. The net effect will depend on the relative size of the two shifts. We will see below that this change in price is an important part of the process of achieving a regulated bioeconomic equilibrium.

A good way to look at this is that $P^*_{\mathrm{AHP}(t)}$ is set by the actions of vessel owners competing against each other to obtain the permits necessary to produce. In order to compete successfully, vessel owners must come up with the highest possible bid price. This is why $D_{\max}$ is used in the equation to calculate the marginal cost of fish. All else equal, the marginal willingness to pay for a unit of AHP will be at its highest level if boats operate the full season. The marginal cost for any level of production will be lower because less effort is used each day. While the incentives operating in a TAC system cause a shortened season, a LAP program provides the opposite incentive.

The demand and supply curves for AHP at our status quo fleet and stock combination are pictured in Figure 7.15. The current equilibrium price occurs at their intersection. It follows that the equilibrium price for AHP will be:

$$\begin{aligned} P^*_{\mathrm{AHP\,(t)}} &= P - \mathrm{MC}\,[\mathrm{TAC}\,(X_t)\,,\ X_t,\ V_t] \\ &= P - \frac{c_i}{qX_t} + \frac{2c_s \mathrm{TAC}\,(X_t)}{\left[V_t D_{\max} q^2 X_t^2\right]} \end{aligned} \tag{7.29}$$

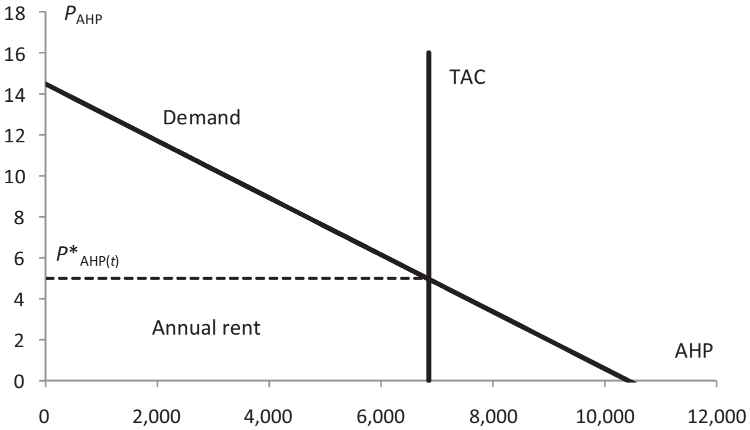

Figure 7.15 Demand and supply curves for annual harvest privileges.

While we go into this in more detail below, the annual rent that is earned for the current fishing year is the total market value of the AHP. It is the difference between the value of the catch and the (minimized) cost of harvesting it.

In summary, AHPs are assets and their value depends on what people are willing to pay for them. The equilibrium price in any period will depend on the sizes of current fleet, the stock, and the TAC. To anticipate the discussion below, in terms of our normal diagram, once the rule for determining the TAC is set, any point in (X, V) space will generate an equilibrium $P^*_{\text{AHP}(t)}$.

7.4.2.4 Profit-maximizing behavior

There is nothing in a LAP program that will change the basic objectives or incentives facing vessel owners. It can still be assumed that they will operate such that they will maximize annual profits. There will be a change in the rules, however, because it will be necessary to acquire or use a unit of AHP for every unit of fish landed. Because of this change, the annual vessel profit function becomes:

$$\prod(\text{LAP})_{v(t)} = D_{\max}\left[P - P^*_{\text{AHP(t)}}\right] q X_t f_t^*(\text{LAP}) - c_i f_t^*(\text{LAP})$$
$$-c_s[f_t^*(\text{LAP})]^2 - \text{FC} \tag{7.30}$$

This is analogous to our regular vessel profit function (see Equation 3.11b), except that the net price of fish, $[P - P^*_{\text{AHP}(t)}]$, is used to determine revenues and the optimal level of daily effort. See equation 7.31. The vessel owner will receive P for selling the fish, but he/she will have to either pay $P^*_{\text{AHP}(t)}$ to acquire the necessary unit of AHP, or forgo the same amount by using a personally owned unit of AHP instead of selling it.

For an individual who owns both a boat and AHP, the issue is to maximize the sum of the net returns to the vessel and the AHP. A decision rule for doing this is to only use personal AHP on the boat if it will earn more than when it is sold on the market. Using Equation 7.30 will accomplish the joint maximization. It is important to note that vessel profits are net of rent earned from ownership of AHP. We will return to this aspect of AHP utilization in more detail below, but for now let us continue the analysis of participant behavior.

Given the vessel profit function with LAPs, the owner will maximize current profits by choosing the optimal amount of the level of daily effort according to the following:

$$
\begin{aligned}
f_t^*\,(\text{LAP}) &= \min\left\{\frac{\left[\left(P - P^*_{\text{AHP}(t)}\right) qX_t - c_i\right]}{2c_s},\ \text{Max } f\right\} \\
&\qquad \text{if } \frac{\left[\left(P - P^*_{\text{AHP}(t)}\right) qX_t - c_i\right]}{2c_s} \geq 0 \\
&= 0 \\
&\qquad \text{if } \frac{\left[\left(P - P^*_{\text{AHP}(t)}\right) qX_t - c_i\right]}{2c_s} < 0
\end{aligned}
\tag{7.31}
$$

This decisional rule is strictly analogous to the general $f^*(X)$ rule above, except that the net price of fish is substituted for the market price (see Equation 3.14).

In the introduction above, it was asserted that the profit-maximizing level of effort produced in a functioning LAP program would be the amount necessary to take the current TAC, given the existing fleet and stock size. Call this the level of daily effort, f_{TAC}. It can be calculated as follows:

$$
f_{\text{TAC}(t)} = \frac{\text{TAC}}{[V_t q D_{\max} X_t]}
\tag{7.32}
$$

While the manipulations are somewhat messy, it is straightforward to show that $f^*{}_t(\text{LAP})$ is equal to $f_{\text{TAC}(t)}$. Substitute Equation 7.29 into Equation 7.31. After simplification, the result is Equation 7.32.

The fact that aggregate effort is kept to the level that will take the TAC is as much due to the assumption of perfect enforcement as it is to the workings of the AHP market. The important thing is the way in which the aggregate effort is produced. There are many ways the necessary effort to take the TAC can be spread over the existing fleet. But the solution generated by the AHP market will result in the lowest possible variable cost of producing the TAC for the given stock and fleet size. Further, this result will occur regardless of the way in which the AHP is distributed. This conclusion will be discussed in more detail below.

7.4.2.5 Formal dynamics with a LAP program

Let us now discuss the full dynamic analysis with a LAP program. We use Figure 7.16 as the basis for the discussion. The similarities to the earlier graphs will be explained below. We start with the assumption that the TAC is constant as

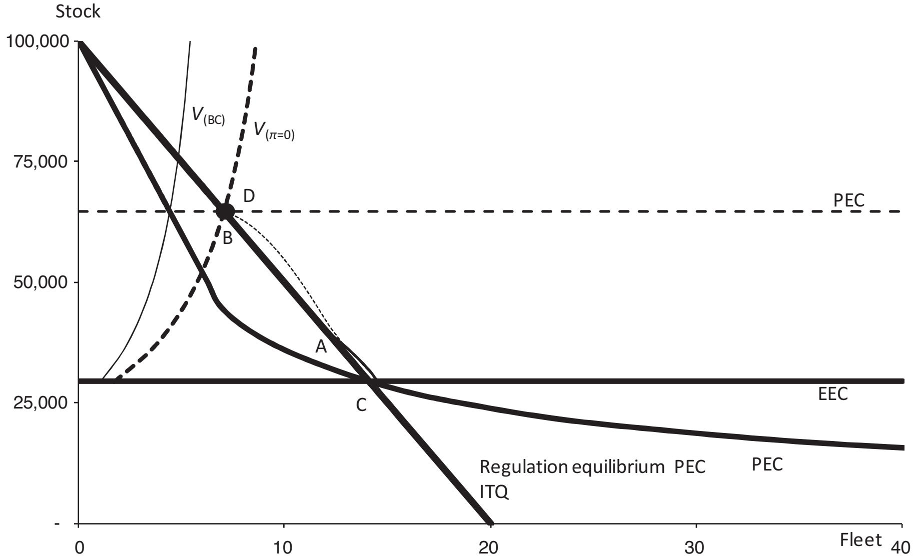

Figure 7.16 Change in PEC, EEC, and trajectory for a LAP program.

in the first TAC analysis in Figure 7.9. We also discuss the case when the TAC varies with stock size as in the second TAC example in Figure 7.12. There are some interesting differences.

The equations of motion are:

$$V_{(t+1)} = V_t + \Phi_1 \pi \, (\text{LAP})_{\text{v(t)}} \tag{7.33}$$

$$X_{(t+1)} = X_t + G(X_t) - V_t q f_t^*(\text{LAP}) X_t \tag{7.34}$$

Again, these are analogous to the previous discussion. They are repeated here to stress the fact that vessel entry and exit in a LAP program is a function of vessel profits net of any rent to the AHP. This is an important point for explaining how the end result is the most efficient fleet possible.

The PEC under the LAP program will be the same as under a TAC program. It will be a horizontal line at the equilibrium stock sizes. With a constant TAC, there will be two curves. There will also be the equivalent of the $V_{(\pi=0)}$ and the $V_{(\text{BC})}$ curves with a LAP program, but they will have different formulations.

The purpose of the $V_{(\text{BC})}$ is to divide the (X, V) space into sections where the TAC is and is not binding. The equation for this curve in a LAP program is:

$$V\,(\text{LAP})_{(\text{BC})} = \frac{\text{TAC}}{(q D_{\max} X \max f)} \tag{7.35}$$

It is different from the equivalent equation for a TAC program because $f^*{}_t(X)$ is replaced by max f. The TAC constraint will not be binding if the existing fleet cannot take the allowable catch when it is operating at $D_{\max}$. Similarly it will not be binding in an LAP probram if the fleet can not take the TAC when daily effort is equal to max f. See Equation 7.31. $V(\text{LAP})_{(\text{BC})}$ is the minimum fleet that is necessary to take the TAC for any level of X.

Recall that the purpose of the $V_{(\pi=0)}$ curve is to divide the (X, V) space into sections where vessel profit is positive or negative so as to be able to discern areas where the fleet will increase or decrease. We know that vessel profits can only equal zero only when it is operated at the minimum of its average cost of effort curve. This occurs when the daily amount of effort is equal to $f_{\min}$ (see Equation 3.9). Therefore, the equation for the zero profit curve under a LAP program is:

$$V(\text{LAP})_{(\pi=0)} = \frac{\text{TAC}}{(f_{\min} q D_{\max} X)} \tag{7.36}$$

At any point on the curve, the optimal level of f from Equation 7.31 will be $f_{\min}$.

The $V(\text{LAP})_{(\pi=0)}$ and the $V(\text{LAP})_{(\text{BC})}$ for this case are pictured in the figure. At all points to the right of the $V(\text{LAP})_{(\pi=0)}$ curve and below the standard EEC, the fleet size will fall. Vessel profits net of the cost of using AHP will be negative. The reverse is true for points to the left of the curve and above the standard EEC.

At any point to the left of the $V(\text{LAP})_{(\text{BC})}$ curve, the TAC is not a binding constraint. Even if the fleet operates at full capacity, it will not take the TAC. In this case, the demand curve for AHP does not intersect the TAC curve in the positive quadrant and so P_{AHP} will equal zero.

As before, because the TAC is not binding to the left of the $V(\text{LAP})_{(\text{BC})}$ curve, the standard PEC should be used to determine the change in stock size. Normally at a point above the new PEC, stock size will fall. However, this will not be the case in the area above the standard PEC and to the left of the $V(\text{LAP})_{(\text{BC})}$ curve. Because the TAC will not be binding, the stock will fall in this area.

To start the analysis of this diagram, let us consider the information that is implicit at each point in (X, V) space, given the necessary components of a LAP regulation program. With a TAC, the assumption of perfect enforcement meant that there was a specific season length associated with each (X, V) combination that would guarantee that the TAC was not surpassed (see Equation 7.16). With a LAP program, the season length remains at $D_{\max}$ and the variable that is controlled by regulation is the level of f. At any combination of X and V, there is a level of f that is necessary to take the TAC (see Equation 7.32). Moreover, we have already established that the market for AHP will generate a P^*_{AHP} that will provide incentives for the fleet to produce at that level.

To go into a little more detail, at any point in (X, V) space, with a LAP program and a given TAC, a movement to the left will mean that the associated f_{TAC} will increase. With fewer vessels, it will take more effort per day to produce the TAC. An upward movement will cause the associated f_{TAC} to decrease. With a higher stock size, the TAC can be taken with less effort per boat.

The point is that there is an endogenous factor which keeps the system going along the correct path. With TACs, perfect enforcement guarantees that the season length will keep actual harvest within the allowable harvest level. With

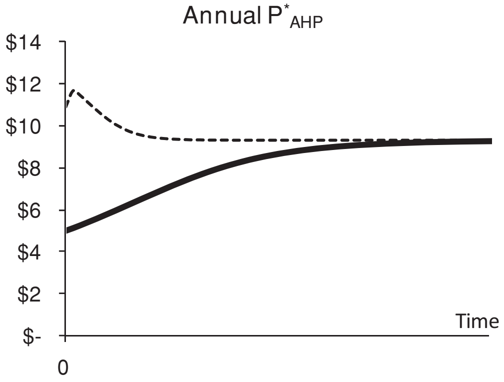

Figure 7.17 Time patterns of the price of annual harvest privileges.

a LAP, perfect enforcement combined with profit-maximizing behavior with transferability guarantees a price for AHP that will keep f at the correct level.

In this case, the trajectory generated using Equations 7.33 and 7.34 goes from the status quo point at A to the illusive point B. The status quo point is to the right of the $V(\text{LAP})_{(\pi=0)}$ curve. With negative returns to vessels, the fleet size will fall. The fishery ends up at the target stock size, and with the most efficient fleet. Different status quo points will have different trajectories but they will all lead to the same bioeconomic equilibrium point. As with the TAC example, if a constant TAC is used, the path to the equilibrium is more abrupt, but given this status quo point, it will reach the same equilibrium. With a status quo point below the lower PEC, the equilibrium will be at the open access equilibrium. The LAP program will not change the results of using a nonbinding TAC.

Along the trajectory the P^*_{AHP} will be continuously changing, and this is the driving force in the system (see Figure 7.17). The change P^*_{AHP} is analogous to the change in season length changing under the TAC program. The solid line represents the price time path for a constant TAC. Note that it originates at the same P^*_{AHP} shown in Figure 7.15. Along the trajectory, the fleet size is falling and the stock size is increasing. The positive effect of the change in stock size on price overpowers the negative effect of the decrease in fleet size, and P^*_{AHP} monotonically increases over time. When the regulated bioeconomic equilibrium is achieved, P^*_{AHP} also reaches a stationary equilibrium value. Since the equilibrium occurs on the $V(\text{LAP})_{(\pi=0)}$ curve, the level of f equals f_{min}. The vessels will be operating at the minimum of the vessel average cost curve. This means that marginal and average cost of effort will be equal. We will have the most efficient fleet operation for the given stock and harvest level. Note from Table 7.3 that the equilibrium average cost of fishing is $7.73. The equilibrium P^*_{AHP} is therefore $9.27, which is the price of fish minus the average cost of fish. Using the above reasoning, the average cost of fish will be equal to the marginal cost of fish. This point will be covered in more detail in the exercises for this chapter.

The dotted line in Figure 7.17 represents the time path of P^*_{AHP} with a variable TAC, where the TAC starts out relatively small and increases with stock size.

The diagram equivalent to Figure 7.17 for this case is discussed in the exercises given in the CD. In this case, the initial P^*_{AHP} is larger than the equilibrium value. This is due to the size of the status quo fleet relative to the now lower TAC. The production of this TAC will call for lower levels of f that will lower the marginal cost of effort. This means the value of AHP is higher because the fish can be produced at a lower cost. But why exactly is P^*_{AHP} temporarily above the equilibrium value? Given the large existing fleet, it is temporarily efficient to use it all with each boat operating at a low level of effort. The vessels can cover their variable costs but they will not cover fixed costs. As the fleet decreases, the efficient level of f will increase and P^*_{AHP} will fall.

Before moving on, let us close this section by returning to the concept of the regulation equilibrium PECs, as summarized in Figure 7.13. They show the regulated equilibrium fleet size that will occur when a given target stock size is achieved by a specific type of regulation. The point that follows from this analysis is that with a LAP program, the regulation equilibrium PEC is the same as PEC[$f_{\min}$] in that figure. No matter what stock size is achieved by the LAP, which of course depends on the size of the TAC, the equilibrium fleet size will be the most efficient one.

7.4.2.6 A closer look at vessel behavior

As promised, let's take a closer look at the joint decision making of a vessel owner who owns AHP permits. We will do so by looking at vessel profit-maximization behavior in terms of fish rather than effort.

It is possible to derive the vessel cost functions in terms of fish in a manner that is analogous to the derivation of the equation for the industry marginal cost of fish. The total vessel cost in terms of effort is:

$$\text{Vessel}\quad \mathrm{TC}(f) = D_{\max}\left[c_i f + c_s f^2\right] + \mathrm{FC} \tag{7.37}$$

Since $\frac{y}{q D_{\max} X_t}$ is the amount of daily effort that is necessary to produce a given level of y, substituting it for f in Equation 7.37 gives a vessel cost function in terms of y for a given stock size.

$$\text{Vessel}\quad \mathrm{TC}(y) = \frac{c_i y}{q X_i} + \frac{c_s y^2}{D_{\max} q^2 X_t^2} + \mathrm{FC} \tag{7.38}$$

The equations for vessel marginal, average, and average variable cost of fish follow directly.

$$\text{Vessel}\quad \mathrm{MC}(y) = \frac{c_i}{q X_t} + \frac{2 c_s y}{D_{\max} q^2 X_t^2} \tag{7.39}$$

$$\mathrm{AC}(y) = \frac{c_i}{q X_t} + \frac{c_s y}{D_{\max} q^2 X_t^2} + \mathrm{FC/y} \tag{7.40}$$

$$\mathrm{AVC}(y) = \frac{c_i}{q X_t} + \frac{c_s y}{D_{\max} q^2 X_t^2} \tag{7.41}$$

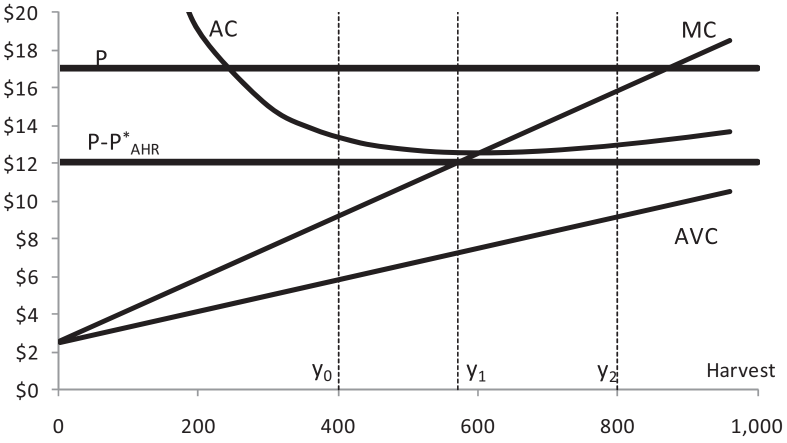

Figure 7.18 Vessel price and cost curves for fish with LAP programs.

Figure 7.18 shows the vessel cost and revenue curves for the status quo situation where the curves are calculated using the above equations. The vessel operator will maximize profits by operating at y_1 where:

$$P - P^*_{\text{AHP}} = \text{MC}\,(y) \tag{7.42}$$

Under open access with no regulation, vessels would operate where $P = \text{MC}(y)$. The LAP program drives a wedge between P and $\text{MC}(y)$ which adds the necessary control on vessel output. The LAP operation rule is easy to see in the case of a vessel owner that does not own any AHP. In order to legally harvest a unit of fish, it is necessary to purchase a unit of AHP. According to Equation 7.42, the vessel operator should increase production of fish until the marginal gains, $[P - P^*_{\text{AHP}}]$, equal the marginal cost of fish. This calls for a production level of y_1.

But what about vessel owners that control an amount of permits that is different from the profit-maximizing amount. Consider a vessel owner that controls y_0 units of AHP. If the owner uses all that AHP, the vessel will be operating at a point where $P - P^*_{\text{AHP}} > \text{MC}(y)$. Therefore, it makes sense to buy more AHP on the market, because the net returns even after paying for the AHP will be positive. It makes sense to continue buying AHP until output is equal to y_1.

Now consider a vessel that controls y_2 units of AHP. If the vessel produced at that level, it would be operating at a point where $P - P^*_{\text{AHP}} < \text{MC}(y)$. This means it would be operating where $P - \text{MC}(y) < P^*_{\text{AHP}}$. The left-hand side is what the vessel is gaining for producing a unit of fish, while the right-hand side is what it could obtain for selling the AHP and giving up the right to take that fish. From a total profit sense, it makes sense to cut back production to y_1 and sell AHP.

In reality, the above sequential view of the process where vessels acting in concert determine the P^*_{AHP} in the open market, and then, operating individually, choose their production level according to Equation 7.42 misses some of the subtleties. Actually, it is a simultaneous process where vessel owners and owners of AHP bargain to buy and sell AHP according to their relative needs for vessel profit maximization and their holdings of AHP, but the net result is the same.

Look at the industry-wide effects of the individual vessel operation. An important question is how the relatively scarce amount of permitted catch is allocated among the existing fleet. If all vessels operate according to Equation 7.42, the marginal cost of fish will be the same for all vessels. This means that the TAC is allocated such that the total cost for producing that level of output is as low as possible. If all boats were not operating at the same MC, it would be possible to shift production from a high-cost boat to a low-cost boat and lower overall cost. This may seem like a small point in terms of our model with homogenous vessels, but the point holds with a heterogeneous fleet as well. This is an important aspect of a LAP program; the competition of AHP leads to cost-minimizing behavior. Even while the fishery is transitioning to a new equilibrium, there will be incentives to allocate the available harvest among the existing fleet so as to minimize costs.

Consider now fishery dynamics in terms of Figure 7.19. In this situation, the vessels are not making profits because the $(P - P^*_{\mathrm{AHP}})$ line is below the average cost curve. The vessels are covering variable costs so they can keep running on a temporary basis, but sooner or later some of them will have to leave the fishery. In the next period, the fleet size will decrease. Although it is not shown on the curve, the stock size will change according to the relative size of the TAC to current stock growth.

As a result of the changes in fleet and stock size, the situation will change in the next period. The vessel cost curves will shift up or down, depending on the change in stock size, and the P^*_{AHP} will change, depending on the relative change in stock and fleet size. An economic equilibrium will be reached when the $(P-P^*_{\mathrm{AHP}})$ line is just tangent to the lowest point of the existing AC(y) curve. The net price will equal both AC(y) and MC(y). The biological equilibrium will occur when the catch from the existing fleet operating at the minimum of the AC(y) is equal to the existing TAC.

As a final point, it must be remembered that it is necessary to make a distinction between the rents which are earned from holding AHPs and the profits from operating the boat. The total rent of AHP at any period is equal to $P^*_{\mathrm{AHP}}{}^*\mathrm{TAC}(X_t)$. Those rents will be earned regardless of whether one operates a vessel or not. Short-term vessel operation and long-term fleet adjustment will be made according to the net returns to the vessel after paying the (real or opportunity) cost of obtaining the necessary AHPs. If the vessel owner considers the rent from AHP ownership when making exit–entry decisions, the process would not result in optimal fleet utilization.

7.4.2.7 The design of LAP programs

The above discussion has covered the basic theory of the workings of a LAP(ITQ) program. There have been many such programs implemented around the world in the last 25 years. None of them are exactly the same. They are designed for different fisheries and are implemented under different types of fisheries laws. They were often designed to accomplish slightly different management objectives. While a description of these different programs and the processes that resulted in their design and implementation would be a useful addition to this discussion, it would be very difficult to summarize succinctly, and there is no room to provide an adequate discussion. There is, however, vast literature on the topic. One is a US Government Document that was cowritten by one of the authors (see Anderson and Holliday, 2007). It is freely available on several web sites and it could be viewed as a useful companion piece to this chapter. Other sources are listed in the References and Suggested Readings.

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Chapter 8

Bioeconomics of ecosystem interdependencies

This chapter introduces a new section of the book where some of the assumptions of analytic and numerical bioeconomic developments presented for single species and single fleet, distributed homogeneously over space in a deterministic context, are relaxed. Managing fisheries with ecosystem considerations involves relevant ecological interdependencies among species along the trophic web. Understanding their dynamics may become essential to further understand fishers' behavior over time. Nevertheless, how far bioeconomic modeling and analysis should go in incorporating multispecies and their bioecological interdependencies will depend on (i) the relevant fisheries and ecosystem management questions posed to address stock recovery and sustainability strategies within an ecosystem framework, (ii) the bioecological and economic data availability for serious parameter estimation of increasingly complex mathematical models required to address the identified relevant questions, and (iii) the assumptions and associated uncertainties of such complex models. With the selected species to be considered in the relevant ecosystem, we have to also consider the heterogeneity of fleets targeting or harvesting them incidentally over time.

Sinclair and Valdimarsson (2003) and Van den Bergh *et al.* (2007) recognized the importance of expanding the single-species bioeconomic approach to include biological and economical interdependencies present in the ecosystem. To address these ecosystem dimensions, in Chapter 9, we will be dealing with the ecological and technological interdependencies of multispecies and multifleet fisheries.

An ecosystem approach to fisheries management has also an inherent spatial dimension: characterizing and understanding its physical and bioecological attributes over space are essential. Knowing the geographic boundaries of population distribution over space, their required habitat, and identifying possible interdependent stocks of the same species linked together by dynamic oceanographic patterns during their life cycle, becomes a major input when trying to design spatial management strategies of single-stock populations and/or metapopulations.

In this ecosystem context, the assumption of homogeneous recruitment distribution over space is relaxed and replaced by functions that distribute recruits in patches of heterogeneous density. This is most relevant for the management of fisheries targeting low mobility or sedentary species.

Introducing the spatial dimension into the bioeconomic analysis requires expanding costs and revenues functions over space to understand and represent fishers' spatial behavior over time. Critical to this analysis is to understand how fishers decide where to fish next, based on previous trips and best dynamic fishing community knowledge of resource availability in alternative fishing sites. Location of ports and corresponding distances to fishing sites become a fundamental input to calculate steaming and fishing costs over space and time. To represent spatial fishing behavior over time then requires calculating quasi profits of variable costs at alternative fishing sites in previous time periods. To address the above, in Chapter 10, we present and discuss the bioeconomics of spatial dynamics in marine fisheries and consider both the situations of single-stock fisheries and metapopulations.

In their contribution in *Science,* Pickitch *et al.* (2004) suggest (i) the need to develop community- and system-level standards, reference points, and control rules similar to single-species decision criteria and (ii) new analytical models and management tools will be needed as well. Multispecies and ecotrophic models must be refined and expanded to better account for system-level uncertainties, to derive system-level reference points, and to evaluate the ecosystem-level consequences of proposed fisheries management actions within an ecosystem context. These authors also suggest that advanced models for ecosystem approaches to fisheries (EAF) should incorporate spatial structure and dynamic environmental processes to properly account for changes in habitat and ecosystem function in the context dynamic fluctuations. Chapter 11 deals with possible stock fluctuations resulting from long-term patterns of environmental variability in the ecosystem that sustain the fishery of interest. It also shows the long-term fishers' behavioral response to fluctuating target stocks and interdependent species.

As acknowledged by Hill *et al.* (2007), marine ecosystems are structurally complex, spatially and temporally variable, and difficult and costly to observe, all of which lead to considerable uncertainty in model predictions. It should be recognized that fisheries scientists have been at the forefront of attempts to account for uncertainty in the management of living resources (Patterson *et al.*, 2001; Harwood and Stokes, 2003; Halpern *et al.*, 2006). However, effort has largely focused on uncertainty in parameter values and the process uncertainty that arises from natural variation, whereas uncertainties about model structure have received less attention.

Because of the greater uncertainties involved in considering ecosystem dimensions than with the single-species approach (see Figure 8.1), the application of decision theory to address situations of limited information seems to be the way to proceed while building appropriate ecosystem information systems. The potential and associated complexities of dealing with growing uncertainties and conducting the corresponding risk analysis for ecosystem approaches to fisheries management are discussed in Chapter 12.

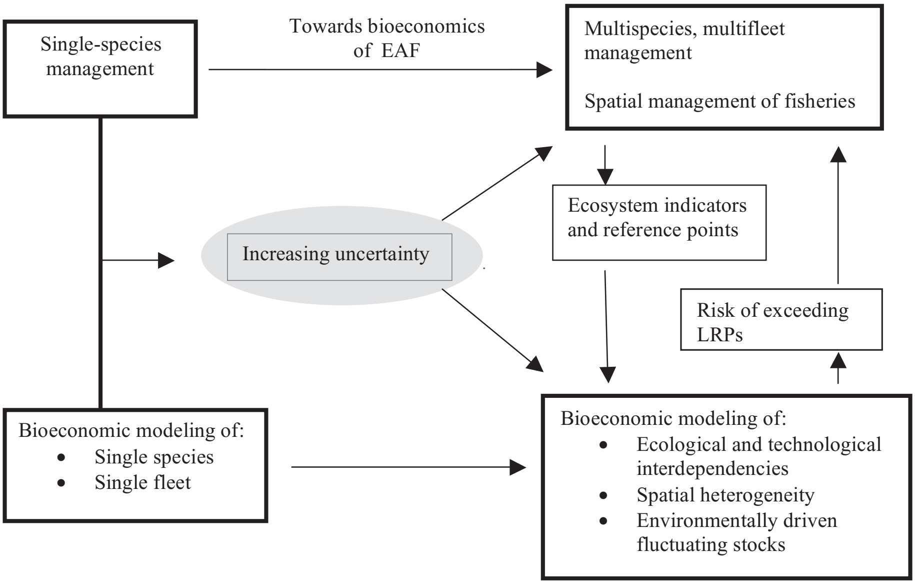

Figure 8.1 A parsimonious bioeconomic approach toward EAF.

The additional complexities and challenges in establishing an EAF to fisheries will not be dealt with in the chapters that follow but are summarized as follows.

8.1 Current challenges of the ecosystems approach to fisheries

Some of the main issues that will need to be dealt with when establishing EAF in coastal states are the following (Seijo, 2007): (i) Changes in management measures to implement an EAF is likely to lead to potential conflicts with stakeholders, and this needs to be considered and allowed for in the process of developing an EAF for specific fisheries; (ii) data collection requirements are greater with the EAF than with single target species analysis of fisheries; (iii) in developing coastal states where it is already difficult to implement adequate data collection for single species, obtaining scientifically valid data in support of fisheries management, following an ecosystem approach, could pose major challenges; (iv) costs of building and maintaining data collection and analysis systems for entire marine ecosystems and its users (i.e., small-scale and industrial fishers, ecotourists, and nonconsumptive users) are likely to be substantial; (v) information costs may need to be paid for by the multiple users of the ecosystem in order to meet the basic requirements for implementing an operational EAF; (vi) managing fisheries taking account of limited knowledge and increasing uncertainties on biotic, abiotic, and human components will require the development of adequate monitoring and risk analysis approaches; (vii) the focus cannot be exclusively on biological monitoring but should also include the human dynamics involving institutional, economic, and social dimensions.

As recognized by Cochrane *et al.* (2004), the implementation of EAF is likely to be slow, and many countries, agencies, and individuals are still in the process of understanding and interpreting just what is intended by the term EAF. The move toward EAF would, in many instances, be on an incremental and adaptive management basis in view of much greater uncertainties and risks. Two aspects that require attention are the time needed to learn and acquire knowledge and the need to carefully assess the distributional implications of EAF interventions. EAF objectives and principles need to be revised and expanded to better reflect social, economic, and institutional implications.

Within this complex framework, it seems relevant to have an indication of the basic steps needed for establishing a parsimonious bioeconomic ecosystem approach to fisheries.

8.1.1 Bioeconomic approach to EAF

The major steps for a bioeconomic approach to ecosystem-based fisheries management may involve the following: (i) define fisheries management questions in the context of multiple users of the marine ecosystem, (ii) identify possible ecological and technological interdependencies among species, habitats, and fisheries within the ecosystem, (iii) select biological/ecological and economic/social performance variables of ecosystem use, (iv) define corresponding ecosystem performance indicators, (v) establish limit and target reference points for the indicators, (vi) identify alternative management, comanagement, and/or community management strategies for the fishery within an ecosystem context, (vii) design a dynamic bioeconomic model of the ecologically and technologically interdependent fishery, (viii) collect data to estimate model parameters, (ix) identify possible states of nature in uncertain and sensitive parameters, (x) build decision tables and apply decision criteria to deal with risk and uncertainty, (xi) estimate probabilities of exceeding ecosystem limit reference points (risks) and of achieving desired target reference points.

In Figure 8.1, we summarize the transition from single-species–single-fleet bioeconomic modeling and analysis toward bioeconomics of EAF.

In this transition from single species to EAF, while still focusing, as is inevitable, on collecting basic data for the economically most important species in the region, their assessments should monitor (i) changes in the abundances of their prey and predators through appropriate survey-based indicators, (ii) changes in the environmental factors of importance to their life histories, and (iii) changes in the dynamics of fishers' and fleets' behavior when targeting predators, preys, and competing species.

To monitor the fishery with a proactive approach to fisheries management, building an operational and useful system of bioeconomic indicators and corresponding reference points is a fundamental step (Seijo, 2006).

8.1.2 Ecosystem indicators and reference points

In the process of extending beyond the single-species approach to fisheries management, the indicators and reference points discussed in Chapter 6 should explicitly account for changes in the ecosystem in which they occur because of either of the following factors:

- Climate changes
- Overfishing
- Environmental degradation due to human activities
- The destruction of critical habitats

But before specifying ecosystem indicators and reference points, as pointed out by Sainsbury and Sumalia (2003), there are two basic questions to answer: (i) Is there a need for explicit reference points for the ecosystem, such as food web dynamics, ecological community structure, and biodiversity, or are species-based reference points sufficient? and (ii) If ecosystem reference points are needed, should they be based on properties of the undisturbed coastal ecosystem? There seems to be an additional question: How to proceed in the absence of baseline studies of early stages of ecosystem use by fishers and other users? Because of the inherent uncertainty of the "original status" of ecosystem habitat and community structure, bioeconomic modeling efforts should be stochastic in nature (see Butterworth and Punt, 2003).

As mentioned in Chapter 6, there are several sources for possible indicators and reference points in the fisheries literature and management plans that can act as a guide in the process, especially for target species. Indicators for objectives relating to the structure and function of the ecosystem and to various aspects of biodiversity are much less developed, but the ecological literature does provide several possible indicators that might be considered, provided that they can be linked to the operational objectives. Also, bioeconomic indicators and corresponding target and limit reference points can be established for ecologically and/or technologically interdependent multispecies and multifleet fisheries (see Figure 8.1). To do so, we will need to take into account both the quality and the availability of current data, and that to be obtained through an enhanced monitoring program of the marine ecosystem in which the multispecies fishery takes place. The development of measures and decision rules should ideally be based on rigorous data analyses, including modeling the dynamics of the fishery within an ecosystem context. Even in data-poor situations, the best available information should be objectively analyzed and considered. In such cases, an extrapolation based on better-studied areas can be used to provide guidance on operational objectives and associated decision rules.

The selection of indicators and reference points should take the technical, management, and operational issues of a given fishery into account. As suggested by FAO (2003), ideally, indicators should reflect parameters that can be measured or estimated with a greater degree of certainty taking into consideration the dynamics of the target population and ecosystem. Selection would also depend on what can be feasibly achieved from the management system and the fishery. At the end of the process, fishery managers and other stakeholders should feel confident that the indicators are both meaningful and workable. Consequently, the selection of indicators and reference points necessarily involves an iterative process—suggesting possibilities and testing them—between all technical participants and stakeholders involved with development of the management plan. As with the selection of operational objectives, there should be a clearly explained basis for selection of the indicator and reference point.

In consistency with precautionary approach to fisheries, lack of scientific certainty should not prevent the selection of indicators and corresponding target and limit reference points that are considered relevant to the fishery and the ecosystem in which it takes place.

8.1.3 Specification of control rules

Based on the information compiled and the setting of operational bioecologic and economic objectives for the multispecies fishery, or the environmentally driven fishery, the next step is to choose a management measure or set of measures for achieving each objective. The use of specific management measures should be accompanied by decision rules on how they are to be applied. The control rules state what management action should be taken under different conditions, often determined by the value of an indicator in relation to a target or limit reference point (FAO, 2003). The decision rules should include how the management measure is to be determined, what data must be collected, and how data will be used to determine the measure.

A number of processes can be used to develop the decision rules. One approach is to set precautionary catch limits on prey species to take account of predators. However, because the precise forms of interactions between species (e.g., predator–prey, competition, mutualism) are usually not well known, the levels of uncertainty will probably become larger when interactions between species are taken into account.

Another approach is to use observed interaction between species in multispecies fishery (e.g., by-catch rate of species 1 when fishing for species 2) to calculate a multispecies vector of allowable catches of target species so that the objectives for nontarget species are achieved.

It should be pointed out that decision rules can be quantitative (e.g., setting catch limits for the prey species under consideration as prespecified fractions of abundance, obtained from surveys, for instance) or qualitative (e.g., a certain value of an indicator call for a decision to conduct a review of the existing fishery management strategy).

To address ecosystem dimensions of fisheries with the parsimonious bioeconomic approach briefly described above, the chapter that follows will discuss the bioeconomics of multispecies multifleet fisheries with technological and ecological interdependencies

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Chapter 9

Ecological and technological interdependencies

As indicated in Chapter 8, steps toward establishing an ecosystem approach to fisheries involve considering the ecological and technological interdependencies among species and resource users, respectively. In previous chapters, we worked with one stock and one fleet, and all theoretical derivation of biomass dynamics, fishermen behavior, and input and output regulations were developed as the basis for adding further complexities of fishery systems. Since the development of the initial chapters, the control variable used has been effort (E) and the state variable to be followed has been stock biomass (X). We will continue to do so in this and the following chapters with corresponding expansions as needed. We also saw in the previous chapters that we can specify effort in bioeconomics equilibrium (E_{BE}), usually called open access equilibrium, effort in maximum economic yield (E_{MEY}), and the resulting levels of stock biomass (X_{BE}, X_{MEY}). Nevertheless, in many fisheries it is important to be able to account for technological interdependencies between fleets when competing for one or more stocks, and also for relevant ecological interdependencies where stocks are interrelated biologically through competition, predation, mutualism, commensalism, or amensalism (Jorgensen, 1994). To be able to answer specific management questions with an ecosystem approach to fisheries management, we need to have the tools that will allow for considering the ecological and technological complexities within a bioeconomic framework of analysis to properly understand the dynamics of resources and resource users in multispecies and multifleet fisheries contexts. In addition, just as we did with the single species and single fleet situations presented in previous chapters, we need to be able to calculate the population equilibrium curves (PECs) and the stock biomass economic equilibrium curves (EECs) that partition the E, X space in four areas where stock biomass and effort can be characterized on whether they are increasing, decreasing, or are at an stable/unstable equilibrium. With ecological and/or technological interdependencies, bioeconomics modeling of fisheries deals with vectors for X, E.

Therefore, in this chapter we will expand the single-species, single-fleet biomass dynamic and age-structured bioeconomic models discussed in Chapters 2–5 to consider multifleet and multispecies fisheries with ecological and/or technological interdependencies among species and fleets. In a parsimonious process toward an ecosystem approach to fisheries management, identifying and considering the relevant bioecological relationship present in a fishery or a set of interdependent fisheries becomes a priority. Also, of importance is to consider possible technologically interdependencies among fleets and among fisheries. That is, the situation of fleets that compete for a stock, multispecies fisheries that harvest incidentally stocks that constitute targets to other fishery, and sequential fisheries where fleets with heterogeneous fishing power, gear selectivity, and costs of effort affect different components of the population structure over time (Charles and Reed, 1985; May *et al.*, 1979).

9.1 Implicit form equations

To develop the implicit form equations for multispecies and multifleet fisheries, we need to acknowledge that we now have two control variables corresponding to effort of Fleet 1 (E_1) and effort of Fleet 2 (E_2), and two state variables for the biomass of Species 1 and 2, X_1 and X_2, respectively.

As a result, we will have a vector of efforts in bioeconomics equilibrium ($E_{1\mathrm{BE}}$, $E_{2\mathrm{BE}}$), a vector of efforts in maximum economic yield ($E_{1\mathrm{MEY}}$, $E_{2\mathrm{MEY}}$), and a vector of state variables for biomass: ($X_{1\mathrm{BE}}$, $X_{2\mathrm{BE}}$) and ($X_{1\mathrm{MEY}}$, $X_{2\mathrm{MEY}}$).

In previous chapters, we had a single growth function curve that was depending on a single stock. In the absence of exploitation, the stock size was K. Now we have two growth functions, each one depending on both species stocks X_1 and X_2.

9.2 Growth functions of ecologically interdependent species

The population growth functions of any two species depend on the abundance of both species and the functional form (reflecting the ecological relationship among them) of these growth functions describing the corresponding interdependencies. This could determine whether we are dealing with a situation of competition, predator–prey, mutualism/symbiosis, commensalisms, or amensalism. The expected population growth of species for these possible ecological interdependencies between two species with biomass X_1 and X_2 is presented in Table 9.1.

In Table 9.1, for the different ecological interdependencies, the change in biomass of one species as a result of a unit change of biomass of the other species is presented as partial derivatives. For competition, a unit increment of biomass of the competitor will result in a negative partial derivative for both species (X_1 and X_2). A unit change of prey biomass (X_2) will result in a positive change in the

Table 9.1 Growth of a species as a result of an increase in biomass of an ecologically interdependent species in the absence of fishing mortality

Ecological interdependence	Species 1	Species 2
Competition	$\partial X_1/\partial X_2 < 0$	$\partial X_2/\partial X_1 < 0$
Predator prey (X_1: predator) (X_2: prey)	$\partial X_1/\partial X_2 > 0$	$\partial X_2/\partial X_1 < 0$
Mutualism/symbiosis	$\partial X_1/\partial X_2 > 0$	$\partial X_2/\partial X_1 > 0$
Commensalism (X_1: commensal)	$\partial X_1/\partial X_2 > 0$	$\partial X_2/\partial X_1 = 0$
Amensalism (X_1: amensal)	$\partial X_1/\partial X_2 < 0$	$\partial X_2/\partial X_1 = 0$

biomass of the predator (X_1). However, a unit increase in biomass of the predator will cause a reduction in prey biomass. Concerning mutualism and symbiosis, as expected, for both species, a unit increase in biomass of one species will increase the biomass of the other. For commensalism, a unit increase of biomass of the host will increase the biomass of the commensal, but an increase in the biomass of the commensals will have no effect on the host biomass. Amensalism, on the other hand, will exhibit a negative change in the amensal for a given unit of change in species X_2. The latter will not be affected by a unit change in amensal biomass.

9.2.1 A general multispecies model: implicit form equations

A general set of implicit form equations for ecological and technological interdependencies is presented as follows.

For illustration purposes, we are now dealing with two species and two fleets (it could, of course, involve more than two of each). Therefore, we have two growth functions, one for Species 1 (G_1) and another for Species 2 (G_2). Therefore, $G_1(X_1, X_2)$ and $G_2(X_1, X_2)$ are the growth functions of Stock 1 and 2 and each are a function of the biologically interdependent stocks biomass X_1 and X_2.

In previous chapters we had a simple short-run yield equation $y = y(E, X)$ for one species and one fleet. Now we have four possible types of yield functions as follows: $y_{11} = y_{11}(E_1, X_1)$, $y_{12} = y_{12}(E_1, X_2)$, $y_{22} = y_{22}(E_2, X_2)$, and $y_{21} = y_{21}(E_2, X_1)$.

Now that we have the growth and the yield functions for the multispecies multifleet fishery, we can have implicit biomass growth functions for both species as follows:

$$\frac{dX_1}{dt} = G_1(X_1, X_2) - y_{11}(E_1, X_1) - y_{12}(E_2, X_1) \tag{9.1}$$

$$\frac{dX_2}{dt} = G_2(X_1, X_2) - y_{22}(E_2, X_2) - y_{21}(E_1, X_2) \tag{9.2}$$

We can now proceed to calculate the population equilibrium curves for X_1 and X_2. It should be mentioned that PECs in the single-stock model are obtained by making $dX/dt = 0$, and solving for X, giving the equilibrium stock size for a given level of effort of the sole fleet. Nevertheless, when we deal with more than one species, we proceed to solve simultaneously for X_1 and X_2 Equations 9.1 and 9.2 by setting them equal to zero, and obtain:

$$PEC_{X_1} = X_1(X_2, E_1, E_2) \tag{9.3}$$

$$PEC_{X_2} = X_2(X_1, E_1, E_2) \tag{9.4}$$

The PECs for the two stocks then give the equilibrium stocks for a given combination of E_1 and E_2. It implies a long-run curve because it requires effort to be maintained constant for a sufficient long period of time (which is a function of the species life cycle) to achieve each equilibrium point in the PEC.

Using the PECs, we can derive the sustainable yield (Y) and sustainable revenue curves (SR) by substituting X_1 and X_2 in the corresponding short-run yield curves to obtain:

$$Y_{11} = q_{11} E_1 X_1(E_1, E_2) \tag{9.5a}$$

$$Y_{12} = q_{12} E_1 X_2(E_1, E_2) \tag{9.5b}$$

$$Y_{22} = q_{22} E_2 X_2(E_1, E_2) \tag{9.5c}$$

$$Y_{21} = q_{21} E_2 X_1(E_1, E_2) \tag{9.5d}$$

The above equation gives us the basis for finding the vectors for each fleet effort in bioeconomic equilibrium ($E_{1\mathrm{BE}}$, $E_{2\mathrm{BE}}$) and effort in maximum economic yield ($E_{1\mathrm{MEY}}$, $E_{2\mathrm{MEY}}$).

Effort in bioeconomic equilibrium for each fleet is obtained by making the profit function of each fleet equal to zero and solving independently for E_1 and E_2. It should be noted that these profit functions are calculated using short-run yield functions. Just to illustrate, consider the situation where one fleet harvest species is X_1 and the other X_2, which are ecologically interdependent. For such a situation, the implicit form equations for profits are:

$$\pi_1 = p_1 y_{11}(E_1, X_1) - c_1 E_1 \tag{9.6}$$

$$\pi_2 = p_2 y_{22}(E_2, X_2) - c_2 E_2 \tag{9.7}$$

Bioeconomic equilibrium level of effort is then obtained by setting Equations 9.6 and 9.7 equal to zero and solving them independently for E_1 and E_2. On the other hand, optimum effort ($E_{1\mathrm{MEY}}$, $E_{2\mathrm{MEY}}$) for both fleets is obtained by finding the partial derivatives with respect to E_1 and E_2 of the sum of fleets' sustained profits and setting them equal to zero. It should be noted these profits use sustainable yield (Y) instead of short-run yield (y), as indicated in the following equations:

$$\frac{\partial \pi}{dE_1} = p_1 q_{11} E_1 X_1(E_1, E_2) + p_2 q_{22} E_2 X_2(E_1, E_2) - c_1 E_1 - c_2 E_2 = 0 \tag{9.8}$$

$$\frac{\partial \pi}{dE_2} = p_1 q_{11} E_1 X_1(E_1, E_2) + p_2 q_{22} E_2 X_2(E_1, E_2) - c_1 E_1 - c_2 E_2 = 0 \tag{9.9}$$

To illustrate how a bioeconomic model can be built to represent ecological interdependencies, this chapter will show two dynamic models and estimate the corresponding PEC and EEC equations, and the optimum and bioeconomic equilibrium levels of effort of the fleets harvesting the species. These models will be for competition and predator–prey interdependencies. Following a similar procedure, bioeconomic models can also be built to represent situations of symbiosis, commensalism, and amensalism described above.

Five possible combinations of technological and ecological interdependencies will be treated in this chapter. For the first four, extensions of the Schaefer–Gordon model will be applied (Figure 9.1). The fifth case will use a dynamic age-structured model to represent a situation where there are two fleets affecting different components of the population structure. The first four cases are described as follows:

Case 1: Two heterogeneous fleets harvest a species that compete with another one for an ecosystem-limiting factor such as space and/or food (Figure 9.1a).
Case 2: One fleet harvests, with a discriminatory fishing gear, a specialized predator, and another fleet targets the corresponding prey (Figure 9.1b).
Case 3: Two fleets with different fishing power and unit costs of effort compete for a stock in the same fishery (Figure 9.1c).
Case 4: A multispecies fishery where a fleet, in addition to its target species, harvests incidentally the target species of another fleet (Figure 9.1d).

We will explore each of the four cases mentioned above by presenting and discussing the following:

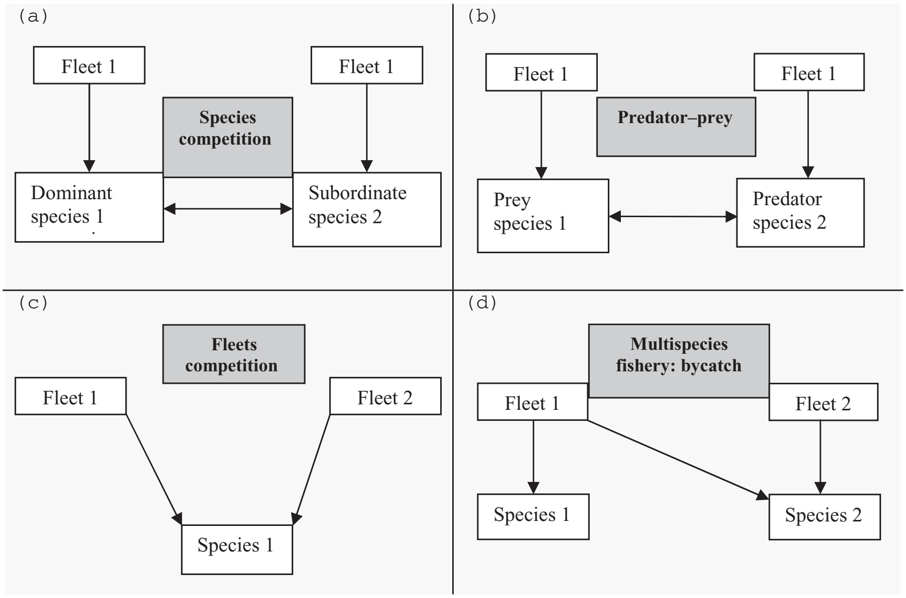


Figure 9.1 Four possible cases in multispecies and multifleet fisheries with ecological and/or technological interdependencies.

1. The open access dynamics of each case to observe the trajectories of biomass, yield, and profits toward equilibrium of different technological interdependencies between fleets and/or different ecological interdependencies among species
2. The PECs for each species, as defined in previous chapters, for the multispecies and/or multifleet fisheries
3. The biomass EECs of the fleets operating in the same ecosystem
4. The effort in bioeconomic equilibrium for each of the fleets
5. The optimum levels of effort for each fleet participating in the fishery or in the interdependent fisheries

It should be pointed out that other possible cases could be explored, in which the same procedure presented above could be applied. In the exercises section of this chapter given in the CD, a small set of management questions are introduced that will require, as in previous chapters, the use of the Excel files provided for each of the cases. These Excel models are prepared for expanding/contracting interdependencies among species and/or fleets.

9.3 Case 1: competition – the Lotka–Volterra model

Concerning resource dynamics, the equations describing the change in biomass of each of the competing species (X_1 and X_2) can be obtained by modifying the logistic model and using the Lotka–Volterra's model (Lotka, 1925; Volterra, 1926):

$$\frac{dX_1}{dt} = r_1 X_1 \left(\frac{K_1 - X_{1,t} - \alpha_{12} X_{2,t}}{K_1} \right) \tag{9.10}$$

$$\frac{dX_2}{dt} = r_2 X_2 \left(\frac{K_2 - X_{2,t} - \alpha_{21} X_{1,t}}{K_2} \right) \tag{9.11}$$

In Equations 9.10 and 9.11, we have two additional parameters α_{12} and α_{21} to account for the interdependence effect of competitor abundance over time. In the numerator of the right-hand side of Equation 9.10, the effect of competing species abundance over time ($X_{2,t}$) is expressed by $\alpha_{12}X_{2,t}$, where α_{12} is the competition interdependence parameter for Species 1. The competition coefficient represents the effect that one species has on the other: α_{12} represents the effect of Species 2 on Species 1, and α_{21} represents the effect of Species 1 on Species 2 (the first number of the subscript always refers to the species being affected). In Equation 9.10 of the Lotka–Volterra model of interspecific competition, the effect that Species 2 has on Species 1 (α_{12}) is multiplied by the population size of Species 2 (X_2). When α_{12} is <1, the effect of Species 2 on Species 1 is less than the effect of Species 1 on its own members. Conversely, when α_{12} is >1, the effect of Species 2 on Species 1 is greater than the effect of Species 1 on its own members. The product of the competition coefficient and the population size of Species 2, $\alpha_{12}X_2$, therefore represents the effect of an equivalent number of individuals of Species 1, and is included in the intraspecific competition, or density-dependence, term. The $\alpha_{21}X_1$ term in Equation 9.11 is interpreted in the same way.

9.3.1 Population isoclines without fishing mortality

With this Lotka–Volterra model, for two competing species, four possible cases can occur depending on their carrying capacities and interdependence coefficients. This can be described by determining the steady-state situation through setting Equations 9.10 and 9.11 equal to zero and solve them for X_1 and X_2, respectively.

$$X_1 = K_1 - \alpha_1 X_2 \tag{9.12}$$

$$X_2 = K_2 - \alpha_2 X_1 \tag{9.13}$$

In Figure 9.2, isoclines for each species are presented showing four possible cases, depending on parameter values of species-carrying capacities (K_1 and K_2) and ecological interdependence coefficients (α_1 and α_2). The word *isocline* is derived from the Greek words for *same slope*. An *isocline* is a line that joins neighboring points with the same gradient, much like a contour line on a map joins all neighboring points of the same height. *Population isoclines* are understood as a set of population sizes at which the rate of change, or partial derivative, for one population in a pair of interacting populations is zero. Equations 9.12 and 9.13 are used to estimate the values of the isoclines as follows: making $X_1 = 0$ in Equation 9.3, we obtain $X_2 = K_1/\alpha_1$, and for $X_2 = 0$, we have $X_1 = K_1$, which is its corresponding carrying capacity. Accordingly, we derive expressions for X_1 and X_2 using Equations 9.13, and obtain $X_1 = K_2/\alpha_2$ and $X_2 = K_2$. Four possible scenarios are shown in Table 9.2.

When the ratios of carrying capacities over competition coefficient (K_1/α_{12}, K_2/α_{21}) are smaller than the corresponding carrying capacities (K_1 and K_2), either species can become the dominant competitor. This situation corresponds to Scenario 1 (Table 9.2).

To illustrate the remaining scenarios of species competition, population isoclines are calculated for competitive exclusion and competitive coexistence.

In Figure 9.2a, we have a scenario where the isocline corresponding to population of Species 1 is below the isoclines of the population of Species 2. In

Table 9.2 Competing species with alternative carrying capacity and interdependence coefficients: without exploitation

	$K_2/\alpha_{21} < K_1$	$K_2/\alpha_{21} > K_1$
$K_1/\alpha_{12} < K_2$	Scenario 1: Either species may dominate	Scenario 2: Species 2 always exclude Species 1
$K_1/\alpha_{12} > K_2$	Scenario 3: Species 1 always exclude Species 2	Scenario 4: Stable coexistence

this situation, the above-described ratio (K_2/α_{21}) is greater than the carrying capacity of Species 1, and the carrying capacity of Species 2 is greater than the ratio (K_1/α_{12}); then Species 2 will always exclude its competitor (i.e., Species 1). Likewise, in Figure 9.2b, an opposite situation will occur. In this new scenario, the ratio (K_1/α_{12}) of Species 1 is greater than the carrying capacity of Species 2

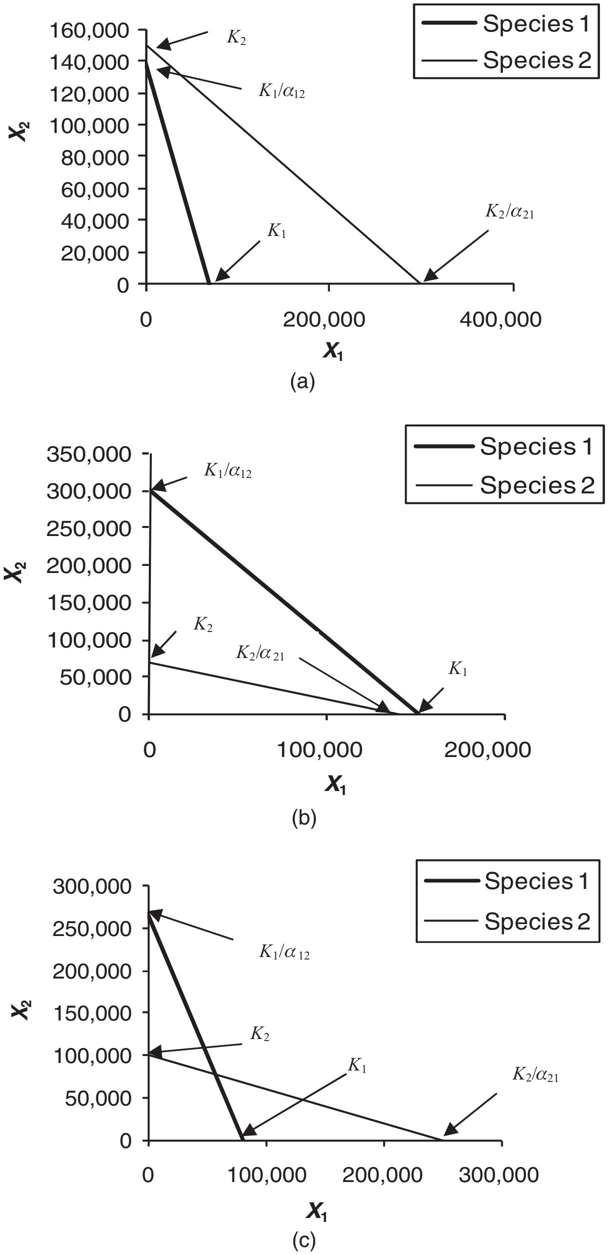


Figure 9.2 Isoclines for possible scenarios of competing species.

Table 9.3 Parameter set for bioeconomic model for three possible species competition scenarios

Parameter	Symbol	Value			Units
		Scenario 1	Scenario 2	Scenario 3	
Carrying capacity – Species 1	K_1	70,000	150,000	80,000	ton
Carrying capacity – Species 2	K_2	150,000	70,000	100,000	ton
Intrinsic rate of growth – Species 1	r_1	0.3	0.2	0.3	1/year
Intrinsic rate of growth – Species 2	r_2	0.2	0.3	0.2	1/year
Competition parameter – Species 1	α_{12}	0.5	0.5	0.3	1/ton
Competition parameter – Species 2	α_{21}	0.5	0.5	0.4	1/ton

and the carrying capacity of Species 1 is greater than the ratio (K_2/α_{21}), and therefore Species 1 will exclude Species 2 from the fishing area. Finally, we have a situation of competitive coexistence (see Figure 9.2c), where the ratios of both species (K_1/α_{12}, K_2/α_{21}) are greater than their corresponding carrying capacities (K_1, K_2). In this situation, we have a stable coexistence of the two species.

Table 9.3 provides parameter sets for the three scenarios explained above without fishing mortality.

9.3.2 Bioeconomics of competition

Once the ecological interdependencies have been identified (e.g., competition), a bioeconomic model can be developed incorporating the biomass natural growth functions and the corresponding catch function to account for fishing mortality of competing species over time. Extending the single-species bioeconomic model presented in Chapter 2 to represent the situation where two fleets harvest competitor species, we obtain a multispecies, multifleet fishery model with species competition built in.

9.3.3 Open access dynamics

As mentioned before, two competition situations may be present: competitive coexistence and competitive exclusion. The first occurs when, in the absence of fishing mortality, the two species coexist with notorious and heterogeneous abundance in the ecosystem. In the second situation, with no fishing mortality, the dominated species is basically absent from the ecosystem.

For a situation like Case 1 mentioned above, the Lotka–Volterra model previously presented is extended to include catch rate of competitors. The biomass growth functions of both species over time are expressed as follows:

$$\frac{dX_1}{dt} = r_1 X_1 \left(\frac{K_1 - X_1 - \alpha_{12} X_2}{K_1} \right) - q_1 E_1 X_1 \tag{9.14}$$

$$\frac{dX_2}{dt} = r_2 X_2 \left(\frac{K_2 - X_2 - \alpha_{21} X_1}{K_2} \right) - q_2 E_2 X_2 \tag{9.15}$$

The equilibrium population curves for species X_1 and X_2 are obtained by making $dX_1/dt = 0$ and $dX_2/dt = 0$, and solving for X_1 and X_2 simultaneously, as follows:

$$X_1 = \frac{K_1r_1r_2 - E_1K_1q_1r_2 - K_2\alpha_{12}r_1r_2 + E_2K_2\alpha_{12}q_2r_1}{r_1r_2 - \alpha_{12}\alpha_{21}r_1r_2} \tag{9.16}$$

$$X_2 = \frac{K_2r_1r_2 - E_2K_2q_2r_1 - K_1\alpha_{21}r_1r_2 + E_1K_1\alpha_{21}q_1r_2}{r_1r_2 - \alpha_{12}\alpha_{21}r_1r_2} \tag{9.17}$$

Effort dynamics of the two fleets is calculated by extending Smith equation presented in Chapter 2 to include the revenues generated by harvesting two competing species:

$$\frac{dE_1}{dt} = \phi_1[E_1(p_1q_1X_1 - c_1)] \tag{9.18}$$

$$\frac{dE_2}{dt} = \phi_2[E_2(p_2q_2X_2 - c_2)] \tag{9.19}$$

where, as before, p, q, and c are species price, catchability coefficient, and the unit cost of effort, respectively, and $\phi > 0$ is the exit–entry parameter of Vernon–Smith equation. Effort is simplified in this chapter to represent the number of vessels fishing the resource at an average number of fishing days per year.

The biomass in EEC for this multispecies fishery of competing species is obtained by making each of the fleets' profits equal to zero ($\pi_1 = 0$ and $\pi_2 = 0$) and solving for X_1 and X_2 as follows:

$$X_1 = \frac{c_1}{p_1q_1} \tag{9.20}$$

$$X_2 = \frac{c_2}{p_2q_2} \tag{9.21}$$

To illustrate the bioeconomic dynamics of competing species, as mentioned before, a case of stable coexistence of two competitors is modeled using the parameter set included in Table 9.4.

In the absence of fishing mortality, the two species coexist with initial biomass levels $X_{2,0} > X_{1,0}$. PECs and EECs and the corresponding bioeconomic equilibrium effort levels for the two fleets harvesting the competitor species ($E_{1\text{BE}}$ and $E_{2\text{BE}}$) are included in Figure 9.3.

These effort values correspond to the point where their average sustainable revenues ($AR_{E1} = p_1Y/E_1$) are equal to their unit costs of effort, which are assumed constant.

9.3.4 Optimum effort

The optimum level of effort for these ecologically interdependent fisheries is obtained by finding the partial derivatives with respect to effort of each fleet of

Table 9.4 Parameter set for a bioeconomic model of competitive coexistence

Parameter	Symbol	Value	Units
Carrying capacity – Species 1	K_1	80,000	ton
Carrying capacity – Species 2	K_2	100,000	ton
Intrinsic rate of growth – Species 1	r_1	0.3	1/year
Intrinsic rate of growth –Species 2	r_2	0.2	1/year
Initial biomass – Species 1	$X_{1,0}$	56,921	ton
Initial biomass – Species 2	$X_{2,0}$	76,932	ton
Competition parameter – Species 1	α_{12}	0.3	1/ton
Competition parameter – Species 2	α_{21}	0.4	1/ton
Catchability coefficient – Species 1	q_1	0.0007	1/vessel/year
Catchability Coefficient – Species 2	q_2	0.0006	1/vessel/year
Unit cost of effort – Fleet 1	C_1	45,000	US$/vessel/year
Unit cost of effort – Fleet 2	C_2	65,000	US$/vessel/year
Price of Species 1	p_1	5,000	US$/ton
Price of Species 2	p_2	5,000	US$/ton
Entry/exit parameter – Fleet 1	ϕ_1	0.0001	vessel/US$
Entry/exit parameter – Fleet 2	ϕ_2	0.0001	vessel/US$

the sum of fleets' profits, setting them equal to zero, and solving for E_1 and E_2, as follows:

$$\frac{\partial \pi}{\partial E_1}\left[p_1 q_1 E_1\left(\frac{K_1 r_1 r_2 - E_1 K_1 q_1 r_2 - K_2 \alpha_{12} r_1 r_2 + E_2 K_2 \alpha_{12} q_2 r_1}{r_1 r_2 - \alpha_{12}\alpha_{21} r_1 r_2}\right) + p_2 q_2 E_2 \right.$$
$$\left. \times \left(\frac{K_2 r_1 r_2 - E_2 K_2 q_2 r_1 - K_1 \alpha_{21} r_1 r_2 + E_1 K_1 \alpha_{21} q_1 r_2}{r_1 r_2 - \alpha_{12}\alpha_{21} r_1 r_2}\right) - c_1 E_1 - c_2 E_2\right] = 0 \tag{9.22}$$

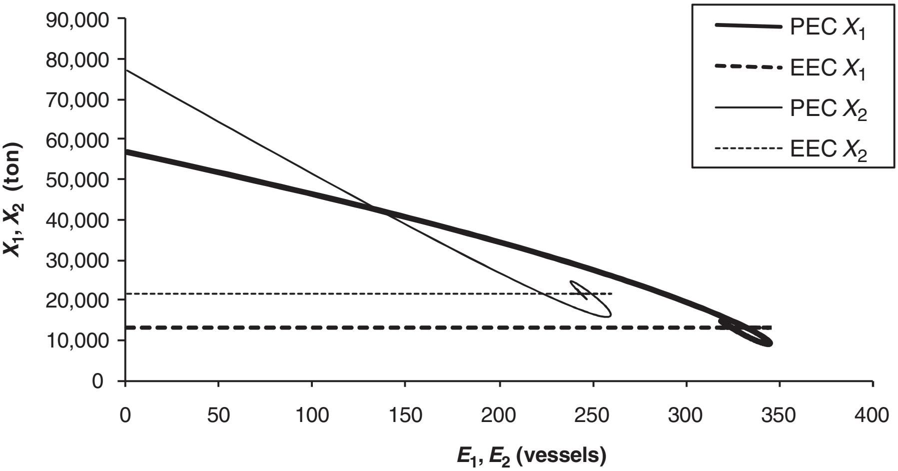


Figure 9.3 Population and economic equilibrium curves for two competing species.

$$\frac{\partial \pi}{\partial E_2}\left[p_1 q_1 E_1\left(\frac{K_1 r_1 r_2 - E_1 K_1 q_1 r_2 - K_2 \alpha_{12} r_1 r_2 + E_2 K_2 \alpha_{12} q_2 r_1}{r_1 r_2 - \alpha_{12}\alpha_{21} r_1 r_2}\right) + p_2 q_2 E_2 \right.$$
$$\left. \times\left(\frac{K_2 r_1 r_2 - E_2 K_2 q_2 r_1 - K_1 \alpha_{21} r_1 r_2 + E_1 K_1 \alpha_{21} q_1 r_2}{r_1 r_2 - \alpha_{12}\alpha_{21} r_1 r_2}\right) - c_1 E_1 - c_2 E_2\right] = 0 \tag{9.23}$$

$$E_{1\mathrm{MEY}} = \frac{\alpha_{12}\alpha_{21} c_1 r_1 r_2 - c_1 r_1 r_2 + K_1 p_1 q_1 r_1 r_2 - K_2 \alpha_{12} p_1 q_1 r_1 r_2 + E_2 K_2 \alpha_{12} p_1 q_1 q_2 r_1 + E_2 K_1 \alpha_{21} p_2 q_1 q_2 r_2}{2 K_1 p_1 q_1^2 r_2} \tag{9.24}$$

$$E_{2\mathrm{MEY}} = \frac{\alpha_{12}\alpha_{21} c_2 r_1 r_2 - c_2 r_1 r_2 + K_2 p_2 q_2 r_1 r_2 - K_1 \alpha_{21} p_2 q_2 r_1 r_2 + E_1 K_2 \alpha_{12} p_1 q_1 q_2 r_1 + E_1 K_1 \alpha_{21} p_2 q_1 q_2 r_2}{2 K_2 p_2 q_2^2 r_1} \tag{9.25}$$

Accordingly, we can estimate effort in bioeconomic equilibrium over time for each of the two fleets ($E_{1\mathrm{BE}}$, $E_{2\mathrm{BE}}$) by making the sustainable profits function of each fleet equal to zero and solving for E_1 and E_2, as follows:

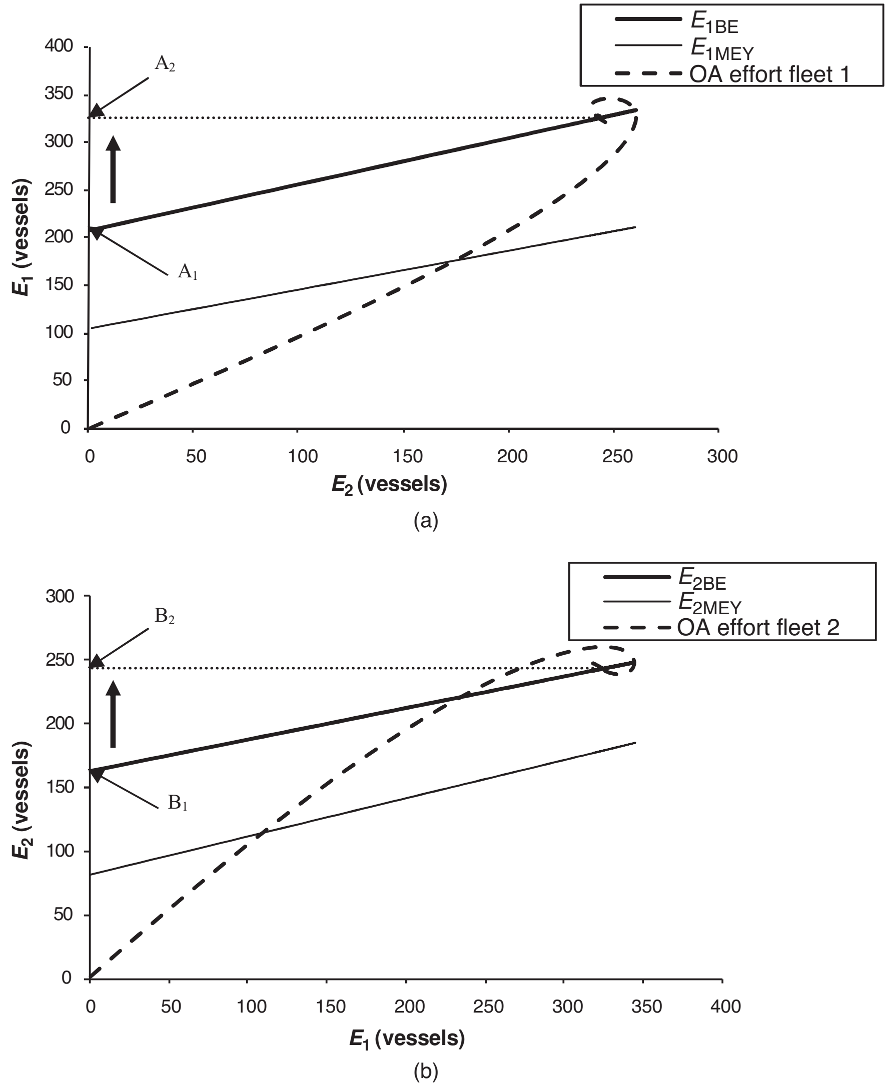
$$E_{1\mathrm{BE}} = \frac{\alpha_{12}\alpha_{21} c_1 r_1 r_2 - c_1 r_1 r_2 + K_1 p_1 q_1 r_1 r_2 - K_2 \alpha_{12} p_1 q_1 r_1 r_2 + E_2 K_2 \alpha_{12} p_1 q_1 q_2 r_1}{K_1 p_1 q_1^2 r_2} \tag{9.26}$$

$$E_{2\mathrm{BE}} = \frac{\alpha_{12}\alpha_{21} c_2 r_1 r_2 - c_2 r_1 r_2 + K_2 p_2 q_2 r_1 r_2 - K_1 \alpha_{21} p_2 q_2 r_1 r_2 + E_1 K_1 \alpha_{21} p_2 q_1 q_2 r_2}{K_2 p_2 q_2^2 r_1} \tag{9.27}$$

For the parameter set of Table 9.4, in Figure 9.4a, we can see magnitudes of effort of Fleet 1 in bioeconomic equilibrium ($E_{1\mathrm{BE}}$) and maximum economic yield ($E_{1\mathrm{MEY}}$) resulting for different effort levels of Fleet 2 (E_2). Accordingly, effort of Fleet 2 in bioeconomic equilibrium ($E_{2\mathrm{BE}}$) and maximum economic yield ($E_{2\mathrm{MEY}}$) for different effort levels of Fleet 1 (E_1) are shown in Figure 9.4b.

Figure 9.4a shows that as the effort of Fleet 2 expands, the open access bioeconomic equilibrium level of effort of Fleet 1 increases from equilibrium effort level A_1 (for $E_2 = 0$) to A_2 as a result of having its target species experiencing greater amounts of available food and/or habitats released by diminishing stock biomass of the competitor. Accordingly, as the effort of Fleet 1 expands, the open access bioeconomic equilibrium level of effort of Fleet 2 increases from equilibrium effort level B_1 (for $E_1 = 0$) to B_2 (see Figure 9.4b).

The optimum level of effort for each fleet is calculated by making the marginal sustainable revenues of each fleet equal to their corresponding unit cost of effort ($\mathrm{MR}_{E1} = \mathrm{MC}_{E1}$ and $\mathrm{MR}_{E2} = \mathrm{MC}_{E2}$) (see Figures 9.5a and 9.5b). Marginal sustainable revenues are estimated by the first derivative of total revenues for



(a)

(b)

Figure 9.4 Bioeconomic equilibrium, maximum economic yield, and open access effort dynamics of one fleet with respect to the other fishing the competing species.

each fleet: $\mathrm{MRE}_1 = \frac{d}{dE_1}[X_1(E_1E_2)p_1q_1E_1]$ and $\mathrm{MRE}_2 = \frac{d}{dE_2}[X_2(E_1E_2)p_2q_2E_2]$. The explicit form equations for calculating MRE_1 and MRE_2 are the following:

$$\mathrm{MRE}_1 = \frac{d}{dE_1}\left[\left(\frac{K_1r_1r_2 - E_1K_1q_1r_2 - K_2\alpha_{12}r_1r_2 + E_2K_2\alpha_{12}q_2r_1}{r_1r_2 - \alpha_{12}\alpha_{21}r_1r_2}\right)p_1q_1E_1\right] \tag{9.28}$$

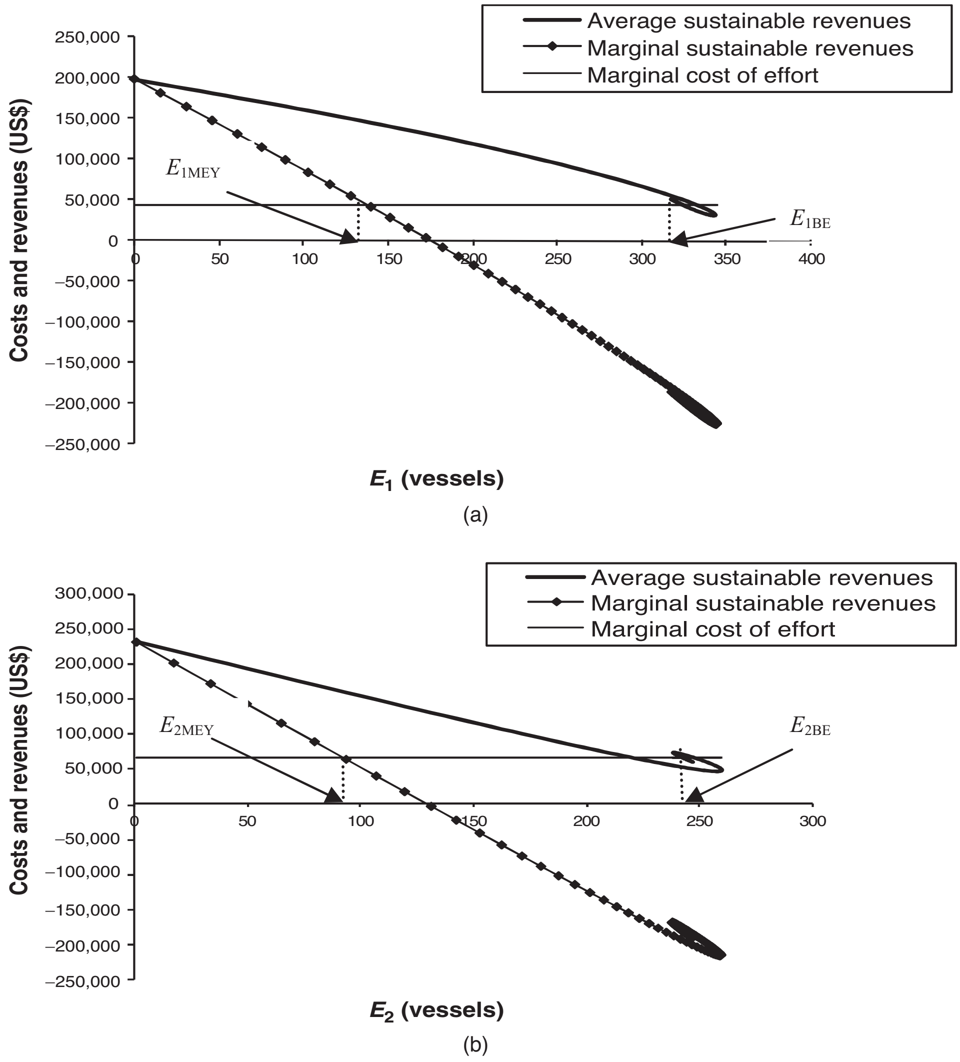


Figure 9.5 Average and marginal sustainable revenues and costs for ecologically interdependent fisheries targeting competing species.

$$\mathrm{MRE}_2 = \frac{d}{dE_2}\left[\left(\frac{K_2 r_1 r_2 - E_2 K_2 q_2 r_1 - K_1 \alpha_{21} r_1 r_2 + E_1 K_1 \alpha_{21} q_1 r_2}{r_1 r_2 - \alpha_{12}\alpha_{21} r_1 r_2}\right) p_2 q_2 E_2\right] \tag{9.29}$$

And, therefore we obtain:

$$\mathrm{MRE}_1 = \frac{p_1 q_1 (K_1 r_1 r_2 - 2E_1 K_1 q_1 r_2 - K_2 \alpha_{12} r_1 r_2 + E_2 K_2 \alpha_{12} q_2 r_1)}{r_1 r_2 \left(\alpha_{12}\alpha_{21} - 1\right)} \tag{9.30}$$

$$\mathrm{MRE}_2 = \frac{p_2 q_2 (K_2 r_1 r_2 - 2E_2 K_2 q_2 r_1 - K_1 \alpha_{21} r_1 r_2 + E_1 K_1 \alpha_{21} q_1 r_2)}{r_1 r_2 (\alpha_{12}\alpha_{21} - 1)} \tag{9.31}$$

In Figures 9.5a and 9.5b, we have E_{BE} and E_{MEY} for each of the fleets, respectively.

The corresponding effort in bioeconomic equilibrium for each of the fleets is consistent with the ones shown in Figures 9.4a (see point A) and 9.4b (see point B), where the open access effort trajectory converges with the E_{BE} curve at the same level of effort shown in Figures 9.5a and 9.5b ($E_{1\mathrm{BE}}$, $E_{2\mathrm{BE}}$, respectively).

9.4 Case 2: bioeconomics of predator–prey interdependencies

9.4.1 Fleets targeting predator and prey

Once predator–prey interdependencies have been identified, a model can be developed by incorporating the corresponding biomass natural growth functions.

Predator–prey interdependencies can be modeled using the Leslie–Gower model (1960). We can have two situations: (1) where only one fleet operates (i.e., vessels targeting the predator or the prey) and (2) when one fleet targets the predator and another the prey. In the section that follows, we will explore, as indicated in the previous section, situation (2).

9.4.2 Population equations

For the prey:

$$\frac{dX_1}{dt} = r_1 X_{1,t}\left(1 - \frac{X_{1,t}}{K_1} - \beta_{12} X_{2,t}\right) - q_1 E_{1,t} X_{1,t} \tag{9.32}$$

For the predator:

$$\frac{dX_2}{dt} = r_2 X_{2,t}\left(1 - \frac{X_{2,t}}{\beta_{21} X_{1,t}}\right) - q_2 E_{2,t} X_{2,t} \tag{9.33}$$

The predation rate to which the prey is subject over time is $r_1 \beta_{12} X_{1,t} X_{2,t}$, in which the interdependence parameter β_{12} multiplies the product of prey and predator population biomasses over time and the intrinsic growth rate of prey population (see numerator of right-hand side of Equation 9.34). Notice that in Equation 9.35, available biomass of the prey multiplied by the interdependence parameter ($\beta_{21} X_{1,t}$) is the equivalent of the carrying capacity for the predator population X_2. Therefore, this model assumes a specialized predator that only consumes species X_1. This is a usual assumption in most predator–prey models. It should be pointed out, however, that the denominator of Equation 9.35 could be extended to also account for consumption of other similar species (even in less amounts) that would involve an additional food source and consequently an additional carrying capacity component.

The equilibrium populations of predators and preys are calculated as before, by making $dX_1/dt = 0$ and $dX_2/dt = 0$ and solving simultaneously for X_1 and X_2.

Therefore, the PECs for the trophically interdependent species when two different fleets target predators and preys are presented in Equations 9.34 and 9.35 as follows:

$$\mathrm{PEC}_{X_1} = \frac{K_1 r_2 (r_1 - E_1 q_1)}{r_1 (r_2 + K_1 \beta_{12} \beta_{21} r_2 - E_2 K_1 \beta_{12} \beta_{21} q_2)} \tag{9.34}$$

$$\mathrm{PEC}_{X_2} = \frac{K_1 \beta_{21} (r_1 - E_1 q_1)(r_2 - E_2 q_2)}{r_1 (r_2 + K_1 \beta_{12} \beta_{21} r_2 - E_2 K_1 \beta_{12} \beta_{21} q_2)} \tag{9.35}$$

As before, we calculate the EEC for this predator–prey fishery where two fleets target these resources by making the profit functions of both fleets equal to zero and solving simultaneously for EEC_{X_1} and EEC_{X_2} as follows:

$$\mathrm{EEC}_{X_1} = \frac{c_1}{p_1 q_1} \tag{9.36}$$

$$\mathrm{EEC}_{X_2} = \frac{c_2}{p_2 q_2} \tag{9.37}$$

PECs and EECs and their corresponding bioeconomic equilibrium effort levels for the two fleets harvesting the prey and predator species, respectively ($E_{1\mathrm{BE}}$ and $E_{2\mathrm{BE}}$), are included in Figure 9.6.

As before, these bioeconomic equilibrium effort values correspond to the point where their average sustainable revenues ($\mathrm{AR}_{E1} = P_1 Y/E_1$) are equal to their unit costs of effort, which is assumed constant.

To illustrate the bioeconomic dynamics of the ecosystem concerning two species with predator–prey relationship and two fleets targeting them, respectively, a parameter set is included in Table 9.5.

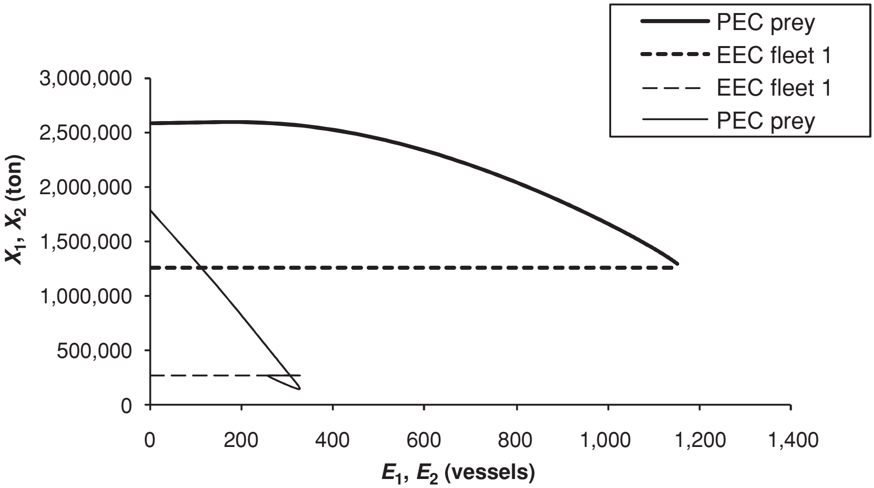


Figure 9.6 Population and economic equilibrium curves for predator and prey species.

Table 9.5 Parameter set for predator–prey model.

Parameter	Symbol	Value	Units
Carrying capacity – prey	K_1	4,000,000	ton
Intrinsic rate of growth – prey	r_1	0.36	1/year
Intrinsic rate of growth – predator	r_2	0.15	1/year
Initial biomass – prey	$X_{1,0}$	4,000,000	ton
Initial biomass – predator	$X_{2,0}$	275,000	ton
Interdependence parameter – prey	β_{12}	0.0000002	1/ton
Interdependence parameter – predator	β_{21}	0.69	1/ton
Catchability coefficient – prey	q_1	0.0002	1/vessel/year
Catchability coefficient – predator	q_2	0.0004	1/vessel/year
Unit cost of effort – Fleet 1	c_1	20,000	US$/vessel/year
Unit cost of effort – Fleet 2	c_2	30,000	US$/vessel/year
Price of Species 1	p_1	80	US$/ton
Price of Species 2	p_2	275	US$/ton
Exit/entry parameter – Fleet 1	Φ_1	0.00095	vessel/US$
Exit/entry parameter – Fleet 2	Φ_2	0.000075	vessel/US$

9.4.3 Optimum effort of Fleets 1 and 2

The optimum level of effort for these predator–prey interdependent fisheries is obtained by finding the partial derivatives with respect to E_1 and E_2 of the sum of fleets' profits and setting them equal to zero:

$$\begin{aligned}\frac{\partial \pi}{\partial E_1}&\left[pq_1E_1\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)\right.\\&\left.+pq_2E_2\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)-c_1E_1-c_2E_2\right]=0\end{aligned} \tag{9.38}$$

$$\begin{aligned}\frac{\partial \pi}{\partial E_2}&\left[pq_1E_1\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)\right.\\&\left.+pq_2E_2\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)-c_1E_1-c_2E_2\right]=0\end{aligned} \tag{9.39}$$

Solving for E_1 and E_2 to obtain the optimum effort levels of the competing fleets, we obtain:

$$\begin{aligned}&E_{1\mathrm{MEY}}=\\&-\frac{c_1r_1r_2-K_1p_1q_1r_1r_2-E_2^2K_1\beta_{21}p_2q_1q_2^2+K_1\beta_{12}\beta_{21}c_1r_1r_2-E_2K_1\beta_{12}\beta_{21}c_1q_2r_1+E_2K_1\beta_{21}p_2q_1q_2r_2}{2K_1p_1q_1^2r_2}\end{aligned} \tag{9.40}$$

$$\begin{aligned}&E_{2\mathrm{MEY}}=\\&\frac{\beta_{12}c_2q_2r_1r_2-p_2q_2^2r_1r_2-\sqrt{\{*\}}+E_1p_2q_1q_2^2r_2+K_1\beta_{12}^2\beta_{21}c_2q_2r_1r_2-K_1\beta_{12}\beta_{21}p_2q_2^2r_1r_2+E_1K_1\beta_{12}\beta_{21}p_2q_1q_2^2r_2}{K_1\beta_{12}\beta_{21}q_2^2(\beta_{12}c_2r_1-p_2q_2r_1+E_1p_2q_1q_2)}\end{aligned} \tag{9.41}$$

where:

$$\sqrt{\{*\}} =$$

$$\sqrt{-q_2^3 r_2 (r_1 - E_1 q_1)(-E_1 \beta_{21} p_1 q_1 K_1^2 \beta_{12}^2 + \beta_{21} p_2 r_2 K_1 \beta_{12} + p_2 r_2)(\beta_{12} c_2 r_1 - p_2 q_2 r_1 + E_1 p_2 q_1 q_2)}$$

Finally, calculate the bioeconomic equilibrium effort function for both fleets by making their corresponding sustainable profits function equal to zero and solving for E_1 and E_2:

$$E_{1\mathrm{BE}} = -\frac{r_1(c_1 r_2 - K_1 p_1 q_1 r_2 + K_1 \beta_{12} \beta_{21} c_1 r_2 - E_2 K_1 \beta_{12} \beta_{21} c_1 q_2)}{K_1 p_1 q_1^2 r_2} \tag{9.42}$$

$$E_{2\mathrm{BE}} = \frac{c_2 r_1 r_2 + K_1 \beta_{12} \beta_{21} c_2 r_1 r_2 - K_1 \beta_{21} p_2 q_2 r_1 r_2 + E_1 K_1 \beta_{21} p_2 q_1 q_2 r_2}{K_1 \beta_{12} \beta_{21} c_2 q_2 r_1 - K_1 \beta_{21} p_2 q_2^2 r_1 + E_1 K_1 \beta_{21} p_2 q_1 q_2^2} \tag{9.43}$$

In Figure 9.7A, we can see that as effort of the fleet targeting the predator expands (i.e., increasing the exploitation rate of predator species), the open access bioeconomic equilibrium level of effort of fleet targeting the prey increases from effort level at A_1 (equilibrium level of effort when $E_2 = 0$) to A_2. This is the result of reducing the predation mortality of prey species targeted by fleet one.

On the other hand (Figure 9.7B), as effort of fleet one, which harvests prey species, expands, the carrying capacity of the predator in the corresponding ecosystem is diminished, causing an open access equilibrium that decreases from point B_1 (equilibrium level of effort when $E_1 = 0$) to B_2.

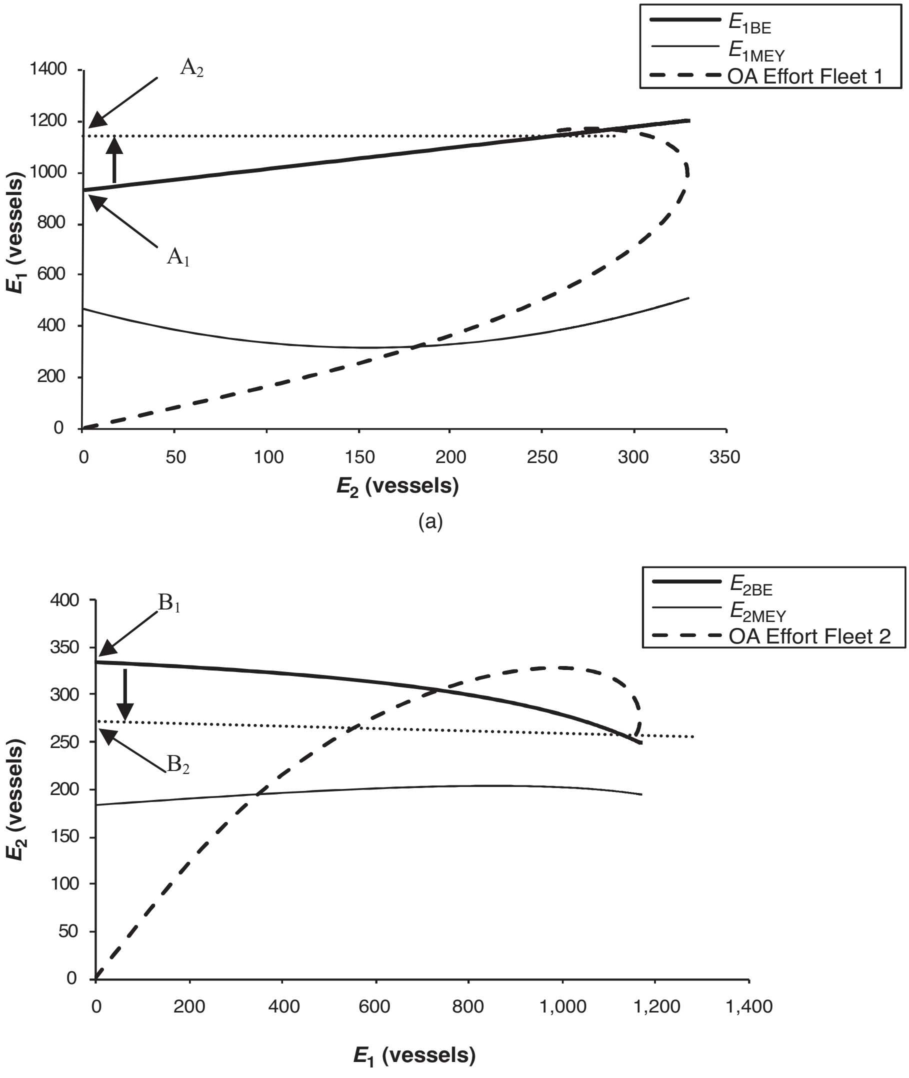
The optimum level of effort for each fleet is calculated by making the marginal sustainable revenues of each fleet equal to their corresponding unit cost of effort ($\mathrm{MR}_{E1} = \mathrm{MC}_{E1}$). As before, marginal sustainable revenues are estimated by the first derivative of total sustainable revenues for each fleet: $\mathrm{MRE}_1 = d[X_1(E_1 E_2) p_1 q_1 E_1]/dE_1$ and $\mathrm{MRE}_2 = d[X_2(E_1 E_2) p_2 q_2 E_2]/dE_2$. The explicit form equations for calculating MRE_1 and MRE_2 are the following:

$$\mathrm{MRE}_1 = \frac{K_1 p_1 q_1 r_2 (r_1 - 2E_1 q_1)}{r_1 (r_2 + K_1 \beta_{12} \beta_{21} r_2 - E_2 K_1 \beta_{12} \beta_{21} q_2)} \tag{9.44}$$

$$\mathrm{MRE}_2 =$$

$$\frac{K_1 \beta_{21} p_2 q_2 (r_1 - E_1 q_1) \left(r_2^2 - 2E_2 q_2 r_2 + K_1 \beta_{12} \beta_{21} r_2^2 + E_2^2 K_1 \beta_{12} \beta_{21} q_2^2 - 2E_2 K_1 \beta_{12} \beta_{21} q_2 r_2\right)}{r_1 (r_2 + K_1 \beta_{12} \beta_{21} r_2 - E_2 K_1 \beta_{12} \beta_{21} q_2)^2} \tag{9.45}$$

In Figures 9.8a and 9.8b, respectively, we have E_{BE} and E_{MEY} for each fleets targeting prey and predator. The corresponding effort in bioeconomic equilibrium for each of the fleets is consistent with the ones shown in Figures 9.7a (see point A) and 9.7b (see point B), where the open access effort trajectory converges with the E_{BE} curve at the same level of effort shown in Figures 9.8a and 9.8b ($E_{1\mathrm{BE}}$, $E_{2\mathrm{BE}}$, respectively).



(a)

(b)

Figure 9.7 Bioeconomic equilibrium, maximum economic yield, and open access effort dynamics of fleets targeting prey and predator as a function of each other's effort.

9.4.4 Biomass isoclines with and without fishing mortality

Using this Leslie–Gower predator–prey model, population isoclines can be described by determining the steady-state situation through setting Equations 9.32 and 9.33 equal to zero and solve them for X_1 and X_2, respectively:

For the prey population equation:

$$X_1 = K_1 - K_1 X_2 \beta_{12} \tag{9.46}$$

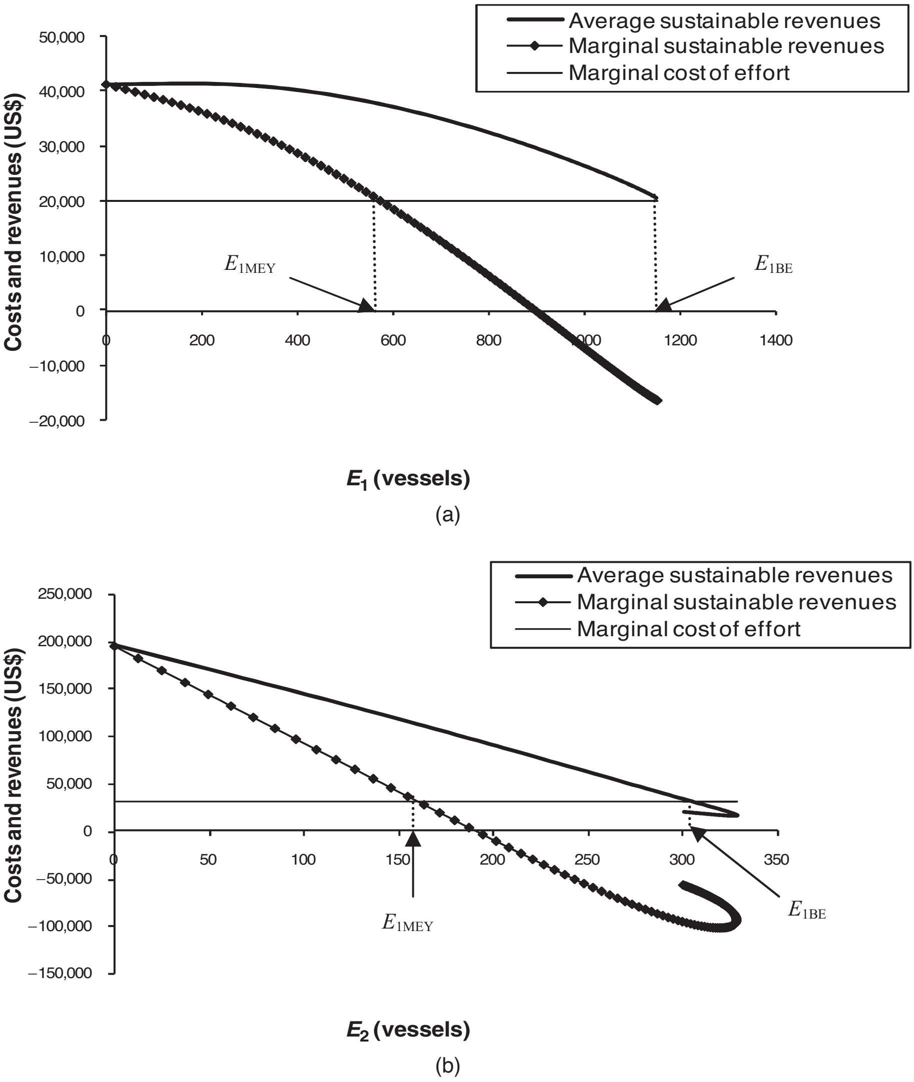


Figure 9.8 Average and marginal sustainable revenues and costs for ecologically interdependent fisheries targeting prey and predator species, respectively.

For the predator population equation:

$$X_2 = \begin{cases} 0 & \text{if } X_1 = 0 \vee \beta_{21} = 0 \\ \text{undefined} & \text{otherwise} \end{cases} \tag{9.47}$$

Making $X_1 = 0$ in Equation 9.46, we obtain $X_2 = 1/\beta_{12}$ and for $X_2 = 0$, we have $X_1 = K_1$, which is the prey-carrying capacity.

As before, with fishing mortality we obtain the following prey equation:

$$X_1 = -\frac{E_1 K_1 q_1 - K_1 r_1 + K_1 X_2 \alpha_1 r_1}{r_1} \tag{9.48}$$

Then, making $X_1 = 0$ in Equation 9.48, we obtain $X_2 = (r_1 - E_1 q_1)/\beta_{12} r_1$, and for $X_2 = 0$, we have $X_1 = K_1 (r_1 - E_1 q_1)/r_1$.

For the exploited predator population, we have:

$$X_2 = -\frac{X_1 \beta_{21} r_2 - E_2 X_1 \beta_{21} q_2}{r_2} \tag{9.49}$$

When making:

$$X_1 = 0 \rightarrow X_2 = 0$$

and:

$$X_2 = 0 \rightarrow X_1 = 0$$

In Figure 9.9, population isoclines in this ecologically interdependent fishery, using prey population Equations 9.46 and 9.48, show exploited and unexploited biomass of predator and prey.

We can observe that for the predator, $1/\beta_{12} > (r_1 - E_1 q_1)/\beta_{12} r_1$, and for the prey, $K_1 > [K_1 (r_1 - E_1 q_1)]/r_1$.

Population isoclines using predator equations, with and without fishing mortality (Equations 9.47 and 9.49), respectively, generates zeros or undefined values because it involves making the prey population biomass equal to zero which constitutes the predator-carrying capacity (see denominator of Equation 9.33).

For further readings on the bioeconomics of predator–prey modeling, see Clark, 1985; Flaaten, 1998.

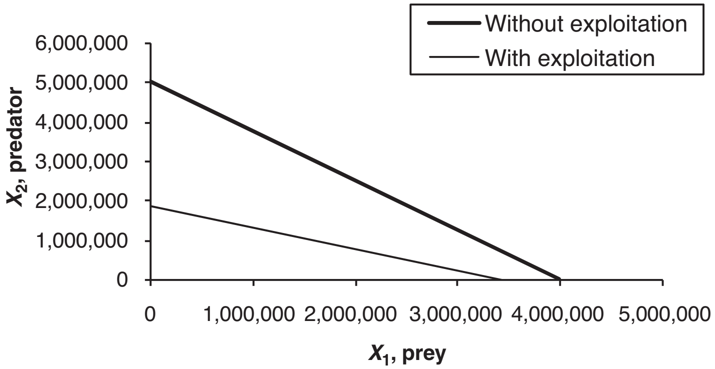


Figure 9.9 Population isoclines with and without fishing mortality from prey population equations.

9.4.5 Extending competition and predator–prey models to ecosystem approaches to fisheries

As mentioned in Chapter 8, in moving in the direction of ecosystem approaches to fisheries management, we can also incorporate in bioeconomic models, general expressions for ecological interdependencies of competition and predator–prey.

In the case of competitors:

$$\frac{dX_i}{dt} = r_i X_i \frac{\left[K_i - X_i - \left(\sum_{j \neq i}^{n} \alpha_{ij} X_j\right)\right]}{K_i} - \sum_{m=1}^{n} q_{m,i} E_{m,i} X_i \tag{9.50}$$

where *ij* are competitors and *m* are different fleets targeting them.

For predator–prey interdependent fisheries with multiple predators and multiple preys, we have the following:

For prey *i* predated by species *j* and harvested by fleet *m*, we have:

$$\frac{dX_i}{dt} = r_i X_i \left[1 - \frac{X_i}{K_i} - \left(\sum_{j}^{n} \beta_{ij} X_j\right)\right] - \sum_{m=1}^{n} q_{m,i} E_{m,i} X_i \tag{9.51}$$

And for predator *j* predating on prey *i* and harvested by fleet *k*, we have:

$$\frac{dX_j}{dt} = r_j X_j \left(1 - \sum_{i}^{n} \frac{X_j}{\beta_{ji} X_i}\right) - \sum_{k=1}^{l} q_{k,j} E_k X_j \tag{9.52}$$

As ecosystem parameters become available, the Excel models used for representing ecological interdependencies can be expanded to include multiple competitors, predators, and preys, as shown in Equations 9.50–9.52. For earlier contributions on the bioeconomics of optimal harvesting of ecologically interdependent fish species; see Hannesson, 1983; Clark, 1985.

9.4.6 Dynamic bioeconomic modeling of technological interdependencies in fisheries

In this section, we will make extensions of the dynamic Shaefer–Gordon model presented in Chapter 3 to represent two more cases: (1) heterogeneous fleets, in terms of fishing power and unit cost of effort, competing for a stock; and (2) multispecies fishery harvesting incidentally a target species of another fishery.

Finally, an age-structured dynamic model is presented to illustrate a sequential fishery where small-scale vessels harvest juveniles in coastal lagoons, estuaries and nearby coastal areas, and industrial fleets targeting adults in deeper waters. For this sequential fishery, it is fundamental to represent the age composition of the catch of each of the fleets in order to properly account for the age-structure effect of their dynamic harvesting rates. In this last case, we will expand the age-structure bioeconomic model discussed in Chapter 5 to introduce the age-specific fishing mortalities and corresponding effort dynamics of small-scale and industrial fleets harvesting different components of the population structure of the same stock.

9.5 Case 3: fleets with heterogeneous fishing power and unit costs of effort competing for a stock

The biomass dynamics equation for a fishery where two fleets compete for a stock is the following:

$$\frac{dX}{dt} = rX\left(1 - \frac{X}{K}\right) - q_1 E_1 X - q_2 E_2 X \tag{9.53}$$

where E_1 and E_2 are the efforts of fleets with heterogeneous fishing power (q_1 and q_2) and unit costs of effort (c_1 and c_2).

Making Equation 9.53 equal to zero and solving for X, we obtain the PEC as follows:

$$\text{PEC}_X = -K\left(\frac{E_1 q_1 - r + E_2 q_2}{r}\right) \tag{9.54}$$

The PEC is determined by its biological parameters (K, r) and the fishing mortalities of the two fleets harvesting the resource.

The rent generated by this stock to each fleet is presented in Equations 9.55 and 9.56:

$$\pi_{E1} = E_1(q_1 Xp - c_1) \tag{9.55}$$

$$\pi_{E2} = E_2(q_2 Xp - c_2) \tag{9.56}$$

The biomass in EEC for each fleet is calculated by making Equations 9.55 and 9.56 equal to zero and solving for X as follows:

$$\text{EEC}_{X_{\text{BE},1}} = \frac{c_1}{q_1 p} \tag{9.57}$$

$$\text{EEC}_{X_{\text{BE},2}} = \frac{c_2}{q_2 p} \tag{9.58}$$

In Figure 9.9, with the parameter set provided (see Table 9.5), we can observe that Fleet 1 excludes Fleet 2 from the fishery. This is so because the biomass at economic equilibrium we have, at which Fleet 2 reaches economic equilibrium (EEC_2), is greater than the biomass at which Fleet 1 reaches it (EEC_1).

With the parameter set provided in Table 9.6, $X_{\text{BE},2} = 2{,}142{,}857$ ton and $X_{\text{BE},1} = 1{,}250{,}000$ ton. Therefore, the critical parameters for defining the direction of the fleet exclusion process, under open access, are the unit cost of effort and the catchability coefficient of each fleet.

Table 9.6 Parameter set for the heterogeneous fleet model

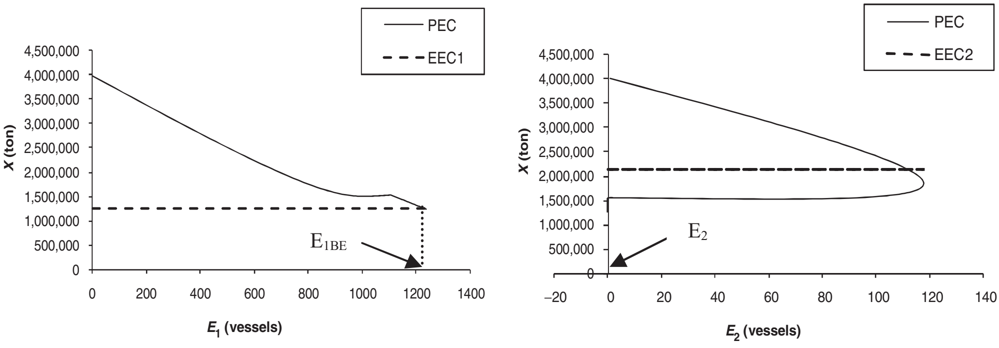
Parameter	Symbol	Value	Units
Carrying capacity	K	4,000,000	ton
Intrinsic growth rate	r	0.36	1/year
Catchability coefficient – small-scale vessel	q_1	0.0002	1/vessel/year
Catchability coefficient – industrial vessel	q_2	0.00035	1/vessel/year
Price of species	p	60	US$/ton
Unit cost of effort – small-scale vessel	c_1	15,000	US$/vessel/year
Unit cost of effort – industrial vessel	c_2	45,000	US$/vessel/year
Initial biomass	X_0	4,000,000	Ton
Exit/entry parameter – small scale	φ_1	0.00175	vessels/US$
Exit/entry parameter – industrial	φ_2	0.0003	vessels/US$

It should be pointed out that under open access, $X_{\mathrm{BE},1} < X_{\mathrm{BE},2}$, and therefore Fleet 1 will tend to exclude Fleet 2 from the fishery. This is so because vessels of Fleet 2 would not be able to remain in the fishery with a lower level of biomass than the one of their bioeconomic equilibrium, as shown by the EEC$_2$ curve. Therefore, E_2 is driven to zero effort (Figure 9.10b), and later on E_1 converges to bioeconomic equilibrium (Figure 9.10a).

9.5.1 Optimum effort of Fleets 1 and 2

The optimum level of effort for the interdependent fisheries is obtained by finding the partial derivatives of the sum of fleets' profits and setting them equal to zero.

$$\begin{aligned}\frac{\partial \pi}{\partial E_1}\Bigg[& pq_1E_1\left(-K\left(\frac{K(E_1q_1 - r + E_2q_2)}{r_1}\right)\right) + pq_2E_2 \\ & \times\left(-K\left(\frac{K(E_1q_1 - r + E_2q_2)}{r_1}\right)\right) - c_1E_1 - c_2E_2\Bigg] = 0 \qquad (9.59)\end{aligned}$$



(a) (b)

Figure 9.10 Population and economic equilibrium curves for heterogeneous fleets competing for a stock.

$$\frac{\partial\pi}{\partial E_2}\left[pq_1E_1\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)+pq_2E_2\right.$$
$$\left.\times\left(-K\left(\frac{K(E_1q_1-r+E_2q_2}{r_1}\right)\right)-c_1E_1-c_2E_2\right]=0 \qquad (9.60)$$

By solving them for E_1 and E_2 to obtain the optimum effort levels of the competing fleets, we have the following:

$$E_{1\mathrm{MEY}}=-\frac{c_1r-Kpq_1r+2E_2Kpq_1q_2}{2Kpq_1^2} \qquad (9.61)$$

$$E_{2\mathrm{MEY}}=-\frac{c_2r-Kpq_2r+2E_1Kpq_1q_2}{2Kpq_2^2} \qquad (9.62)$$

The effort in economic equilibrium for these two fleets will result in the exclusion of one of the fleets in the long run, and, as mentioned before, it will depend on the relative values of their unit costs of effort and catchabilities.

Effort in bioeconomic equilibrium is calculated, as before, by making the sustainable profit functions of both fleets equal to zero and solving them for E_1 and E_2, respectively.

$$E_{1\mathrm{BE}}=-\frac{c_1r-Kpq_1r+E_2Kpq_1q_2}{Kpq_1^2} \qquad (9.63)$$

$$E_{2\mathrm{BE}}=-\frac{c_2r-Kpq_2r+E_1Kpq_1q_2}{Kpq_2^2} \qquad (9.64)$$

The optimum level of effort for each fleet is calculated by making the marginal sustainable revenue equal to their corresponding unit cost of effort ($\mathrm{MR}_{E1}=\mathrm{MC}_{E1}$). As before, marginal sustainable revenues are estimated by the first derivative of total sustainable revenues for each fleet: $\mathrm{MRE}_1=d[X(E_1E_2)pq_1E_1]/dE_1$ and $\mathrm{MRE}_2=d[X(E_1E_2)pq_2E_2]/dE_2$. The explicit form equations for calculating MRE_1 and MRE_2 are the following:

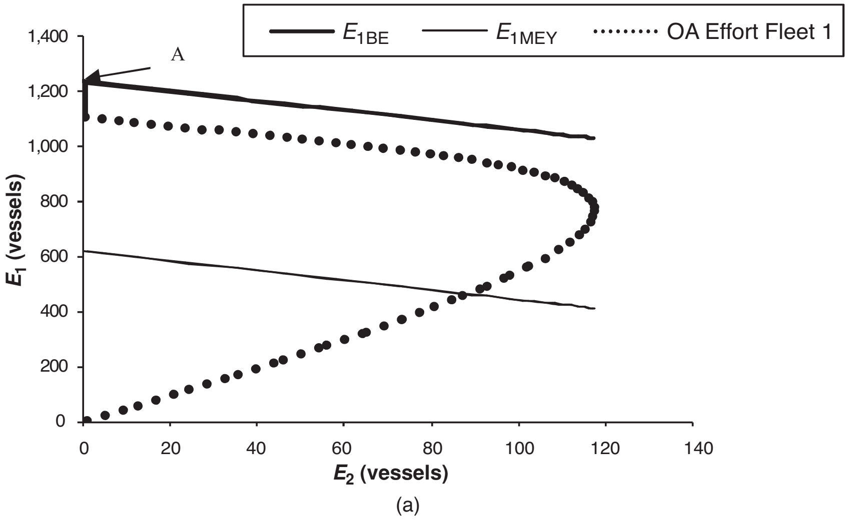
$$\mathrm{MRE}_1=-\frac{Kpq_1(2E_1q_1-r+E_2q_2)}{r} \qquad (9.65)$$

$$\mathrm{MRE}_2=-\frac{Kpq_2(E_1q_1-r+2E_2q_2)}{r} \qquad (9.66)$$

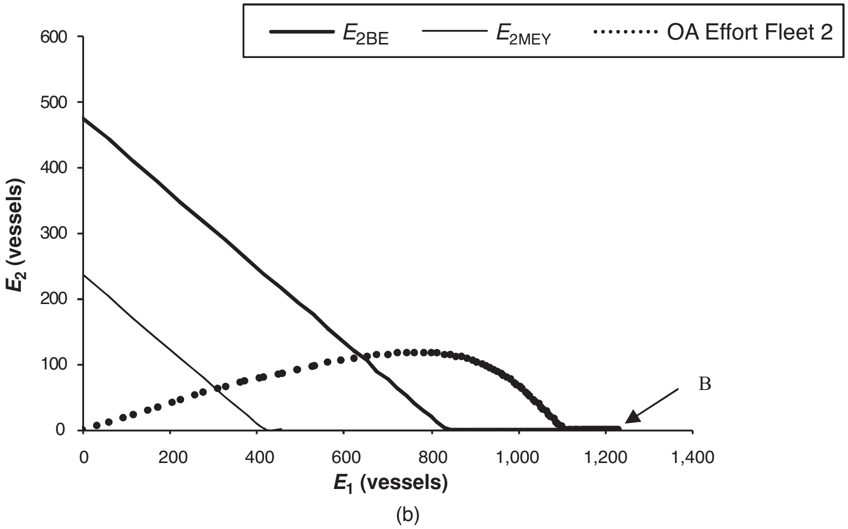
In Figure 9.10, we can observe that as the effort of one of the fleets increase, the effort in bioeconomic equilibrium and maximum economic yield of the other fleet tend to decrease, because they are competing for the same stock. Notice that in the previous cases of ecological interdependencies, we had different trends. In the case of species competition, as the effort of one fleet increased, E_{BE} and E_{MEY} for the other fleet also increased because a higher exploitation rate of the former released the species competing factor (food and/or habitat), allowing the ecosystem to support higher levels of biomass of the latter competing species.

In the case of the predator–prey model described above, as effort to harvest the predator increases, the bioeconomic equilibrium and maximum economic yield for the fleet targeting the prey also increase because predation rate was decreasing as exploitation rate of predators increase. But when the effort to harvest the prey species increases, the corresponding effort in BE and MEY of the fleet targeting the predator tends to decrease because of diminishing prey abundance that constitutes its carrying capacity.

Figure 9.11 shows the fleet exclusion process that occurs when heterogeneous vessels compete for the same stock under open access conditions. The open access

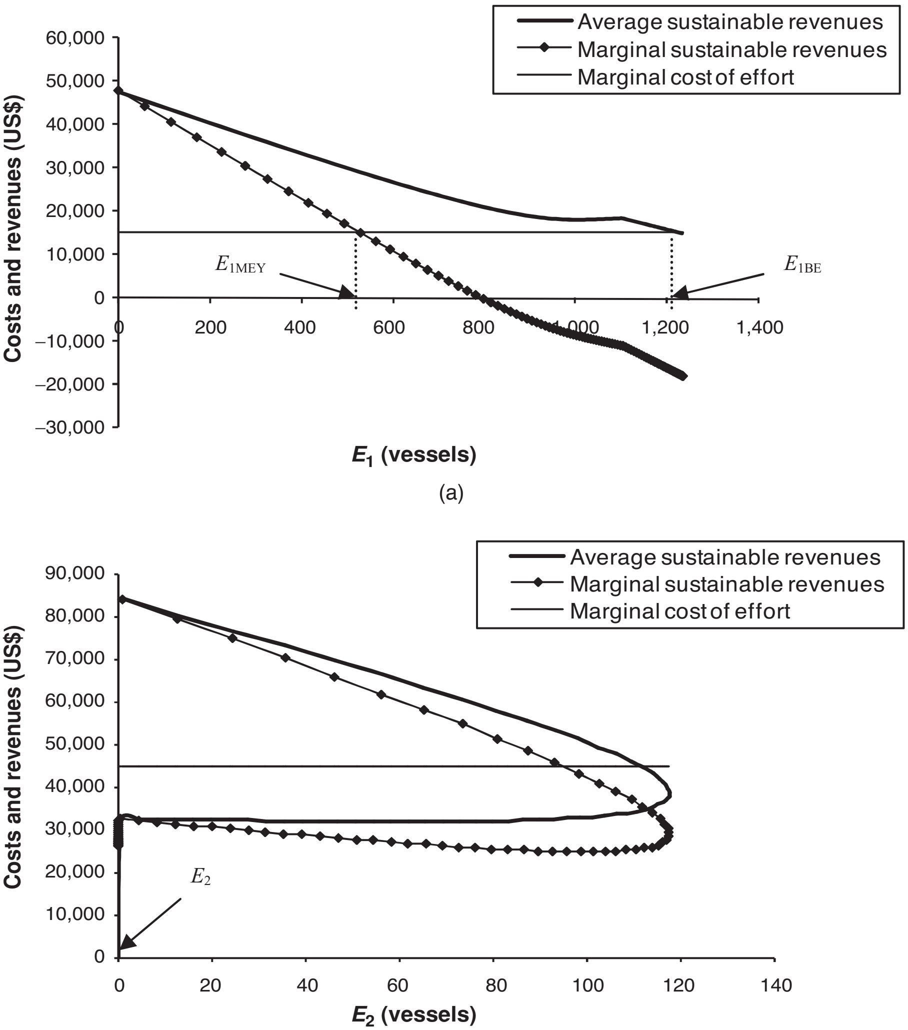


(a)



(b)

Figure 9.11 Bioeconomic equilibrium, maximum economic yield, and open access effort dynamics of heterogeneous fleets competing for a stock.



(a)

(b)

Figure 9.12 Average and marginal sustainable revenues and costs of heterogeneous fleets targeting the same stock.

dynamics of the dominant fleet E_1 exhibits a backward-bending trajectory (Figure 9.11a). This trajectory reflects the exclusion process of fleet E_2 and the final convergence of E_1 to its bioeconomic equilibrium (point A). Figure 9.11b shows the open access trajectory of Fleet 2 toward its exclusion from the fishery (point B). The bioeconomic equilibrium level of effort for Fleet 1 ($E_{1\mathrm{BE}}$) is consistent with the one calculated by making $\mathrm{AR}_{E1} = \mathrm{AC}_{E1}$, shown in Figure 9.12a.

When effort of dominant Fleet 1 reaches 1,100 units, the open access effort of Fleet 2 becomes zero. In Figure 9.12b, average and marginal sustainable revenues of Fleet 2 behave in a forward-bending trajectory that goes beyond its BE level of effort, as the open access dynamics of the dominant fleet continues to increase and excludes vessels of Fleet 2 toward zero effort level.

9.5.2 Effort isoclines: heterogeneous fleets

In the bioeconomics of isoclines for a fishery where two fleets compete for a stock, we obtain isoclines for effort in maximum economic yield and bioeconomic equilibrium.

By making E_2 equal to zero in Equation 9.61, we have an expression for the maximum economic yield isocline for Fleet 1 ($\mathrm{MEYI}_{E1,1}$):

$$\mathrm{MEYI}_{E1,1} = -\frac{c_1 r - Kpq_1 r}{2Kpq_1^2} \tag{9.67}$$

Accordingly, we obtain the maximum economic yield isocline for Fleet 2 ($\mathrm{MEYI}_{E1,2}$) by making the same Equation 9.61 ($E_{1\mathrm{MEY}}$) equal to zero and solving for E_2:

$$\mathrm{MEYI}_{E1,2} = -\frac{0.5(c_1 r - Kpq_1 r)}{Kpq_1 q_2} \tag{9.68}$$

As before, by making E_1 equal to zero in Equation 9.62, we have the maximum economic yield isocline for Fleet 2 ($\mathrm{MEYI}_{E2,2}$). Again, the maximum economic yield isocline for Fleet 1 ($\mathrm{MEYI}_{E2,1}$) is obtained by making the same Equation 9.62 ($E_{2\mathrm{MEY}}$) equal to zero and solving for E_1:

$$\mathrm{MEYI}_{E2,2} = -\frac{c_2 r - Kpq_2 r}{2Kpq_2^2} \tag{9.69}$$

$$\mathrm{MEYI}_{E2,1} = -\frac{0.5(c_2 r - Kpq_2 r)}{Kpq_1 q_2} \tag{9.70}$$

Continuing with the same process, the bioeconomic equilibrium isocline for Fleet 1 is obtained by making E_2 equal to zero in Equation 9.63:

$$\mathrm{BEI}_{E1,1} = -\frac{c_1 r - Kpq_1 r}{Kpq_1^2} \tag{9.71}$$

Accordingly, we calculate the bioeconomic equilibrium isocline for Fleet 2 ($\mathrm{BEI}_{E1,2}$) by making the same Equation 9.63 ($E_{1\mathrm{BE}}$) equal to zero and solving for E_2 as follows:

$$\mathrm{BEI}_{E1,2} = -\frac{c_1 r - Kpq_1 r}{Kpq_1 q_2} \tag{9.72}$$

Finally, by making E_1 equal to zero in Equation 9.64 ($E_{2\mathrm{BE}}$), we have the bioeconomic equilibrium isocline for Fleet 2 ($\mathrm{BEI}_{E2,2}$). And, by equating to zero

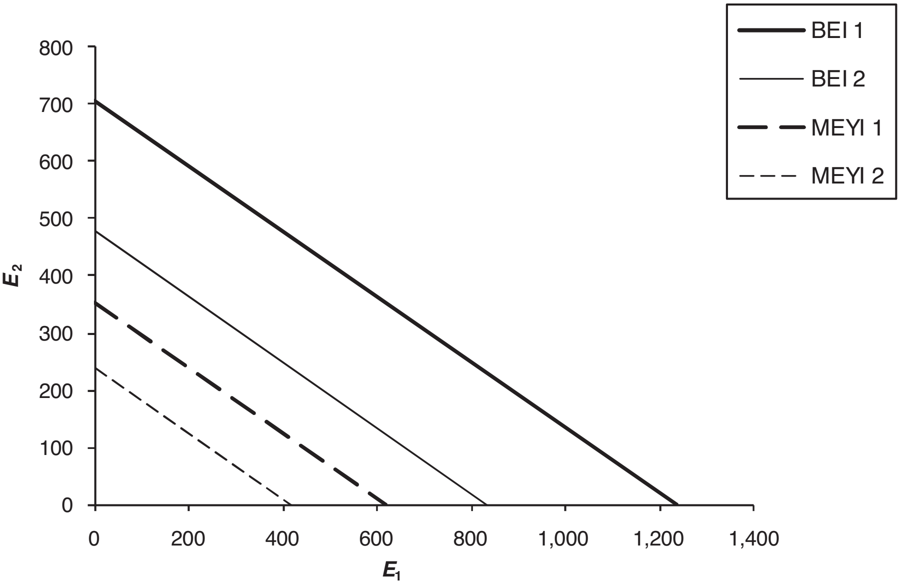


Figure 9.13 Bioeconomics of isoclines of heterogeneous fleets competing for a stock.

expression 9.64 and solving for E_1, we have a bioeconomic equilibrium isocline for Fleet 1 ($\mathrm{BEI}_{E2,1}$):

$$\mathrm{BEI}_{E2,2} = -\frac{c_2 r - Kpq_2 r}{Kpq_1 q_2} \tag{9.73}$$

$$\mathrm{BEI}_{E2,1} = -\frac{c_2 r - Kpq_2 r}{Kpq_2^2} \tag{9.74}$$

The resulting values are presented in Figure 9.13, where we can clearly see that Fleet 1 excludes Fleet 2.

9.6 Case 4: multispecies and multifleet fishery – a fleet harvesting incidentally target species of another fishery

Consider the case of a multispecies fishery with Fleet 1 targeting Species 1 and harvesting incidentally Species 2, which in turn is targeted by Fleet 2. This is the case of many coastal fisheries where one fleet uses a nondiscriminatory fishing gear and harvest incidentally a diversity of species that may constitute target species of other fleets.

In this type of fishery, we can have two situations: (1) Species 2 can remain in the ecosystem for exploitation by Fleet 2 as long as the fishing mortality caused by the incidental harvest of Fleet 1 is smaller than the intrinsic growth rate of Species 2 ($q_{12}E_{2\mathrm{BE}} < r_2$); and (2) Fleet 1 that targets Species 1 and incidentally harvest Species 2 may exhaust Species 2, if the incidental fishing mortality of Species 2 at bioeconomic equilibrium level of effort of Fleet 1 is greater than the intrinsic growth rate of Species 2 ($q_{12}E_{2\mathrm{BE}} > r_2$). In this section, we will use parameters for situation (1).

The biomass dynamics equations for Species 1 and 2 are the following:

$$\frac{dX_1}{dt} = r_1 X_1 \left(1 - \frac{X_1}{K_1}\right) - q_{11} E_1 X_1 \tag{9.75}$$

$$\frac{dX_2}{dt} = r_2 X_2 \left(1 - \frac{X_2}{K_2}\right) - q_{12} E_1 X_2 - q_{22} E_2 X_2 \tag{9.76}$$

where E_1 and E_2 are the efforts of Fleets 1 and 2, respectively, and q_{11} and q_{12} are the catchability coefficients for target (X_1) and incidental (X_2) harvest of Fleet 1, and q_{22} the corresponding catchability of species X_2 that is targeted by Fleet 2.

The PECs of this multispecies fishery are calculated as before by making $dX_1/dt = 0$ and $dX_2/dt = 0$, and solving simultaneously for X_1 and X_2.

The PECs for the technologically interdependent fisheries when a fleet targets one species, and incidentally harvest the target species of another fishery is then presented in Equations 9.77 and 9.78:

$$\mathrm{PEC}_{X_1} = \frac{K_1(r_1 - E_1 q_{11})}{r_1} \tag{9.77}$$

$$\mathrm{PEC}_{X_2} = -\frac{K_2(E_1 q_{12} - r_2 + E_2 q_{22})}{r_2} \tag{9.78}$$

The biomass EECs for Species 1 and 2 are obtained by setting equal to zero the corresponding profit function Equations 9.79 and 9.80 of this multispecies, multifleet fishery:

$$\pi_1 = E_1(p_1 q_1 X_1 + p_2 q_1 X_2 - c_1) \tag{9.79}$$

$$\pi_2 = E_2(p_2 q_2 X_2 - c_2) \tag{9.80}$$

and solving for X_1 and X_2 as follows:

$$\mathrm{EEC}_{X_1} = \frac{c_1 - X_2 p_2 q_{12}}{p_1 q_{11}} \tag{9.81}$$

$$\mathrm{EEC}_{X_2} = \frac{c_2}{p_2 q_{22}} \tag{9.82}$$

In Figure 9.14, we have the EEC and PEC curves for target species biomass of Fleets 1 and 2 (X_1 and X_2) and the corresponding bioeconomic equilibrium effort of each fleet.

9.6.1 Optimum levels of effort

The optimum level of effort for these interdependent fisheries is obtained by finding the partial derivatives of the sum of profits and setting them equal to

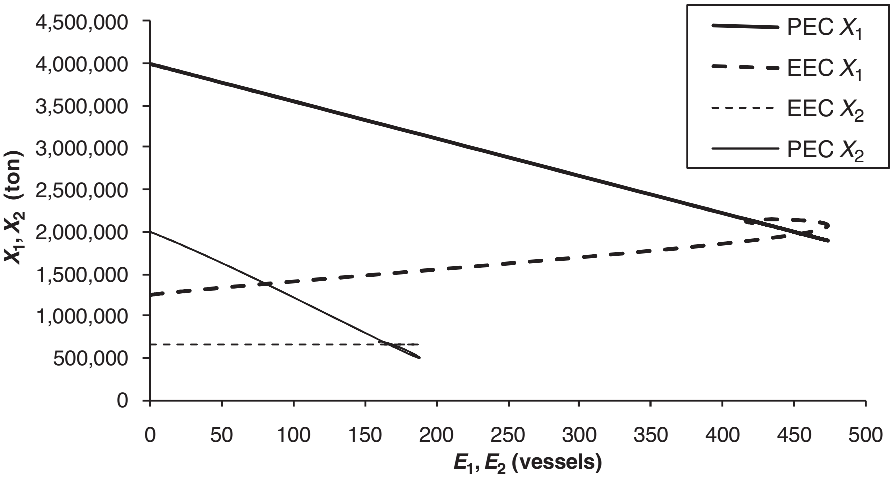


Figure 9.14 Population and economic equilibrium curves for a multispecies fishery.

zero as follows:

$$\frac{\partial}{\partial E_1}\left[\left(\frac{K_1(r_1 - E_1 q_{11})}{r_1}\right) p_1 q_{11} E_1 + \left(-\frac{K_2(E_1 q_{12} - r_2 + E_2 q_{22})}{r_1}\right) p_2 q_{12} E_1 \right.$$
$$\left. + \left(-\frac{K_2(E_1 q_{12} - r_2 + E_2 q_{22})}{r_1}\right) p_2 q_{22} E_2 - c_1 E_1 - c_2 E_2\right] = 0 \qquad (9.83)$$

$$\frac{\partial}{\partial E_2}\left[\left(\frac{K_1(r_1 - E_1 q_{11})}{r_1}\right) p_1 q_{11} E_1 + \left(-\frac{K_2(E_1 q_{12} - r_2 + E_2 q_{22})}{r_1}\right) p_2 q_{12} E_1 \right.$$
$$\left. + \left(-\frac{K_2(E_1 q_{12} - r_2 + E_2 q_{22})}{r_1}\right) p_2 q_{22} E_2 - c_1 E_1 - c_2 E_2\right] = 0 \qquad (9.84)$$

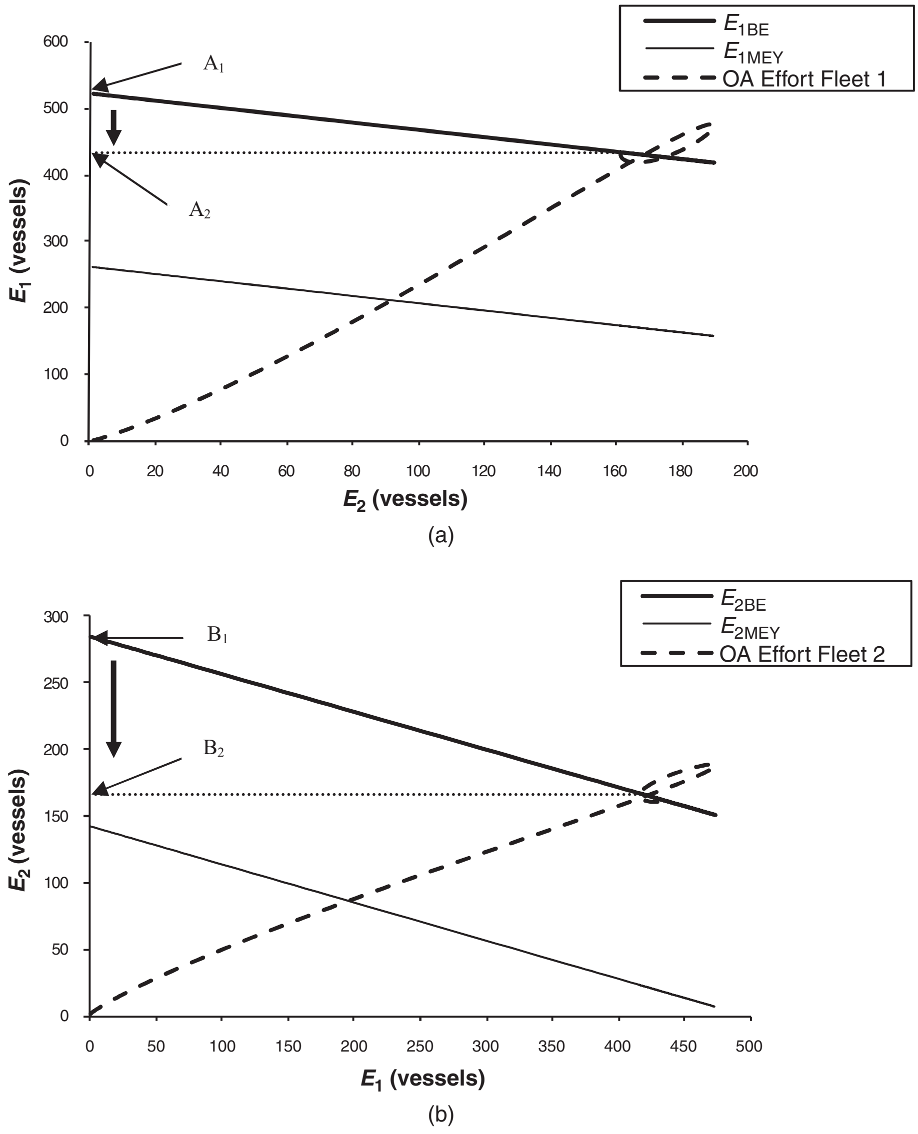
and solving them for E_1 and E_2, as follows:

$$E_{1\text{MEY}} = -\frac{c_1 r_1 r_2 - K_1 p_1 q_{11} r_1 r_2 - K_2 p_2 q_{12} r_1 r_2 + 2 E_2 K_2 p_2 q_{12} q_{22} r_1}{2(K_1 p_1 r_2 q_{11}^2 + K_2 p_2 r_1 q_{12}^2)} \qquad (9.85)$$

$$E_{2\text{MEY}} = -\frac{c_2 r_2 - K_2 p_2 q_{22} r_2 + 2 E_1 K_2 p_2 q_{12} q_{22}}{2 K_2 p_2 q_{22}^2} \qquad (9.86)$$

We can observe that, under open access, Fleet 1 harvesting incidentally Species 2 in this multispecies fishery will generate a negative externality to Fleet 2 that targets the less abundant and less value Species 2 (Figure 9.14). Fleet 1 and Fleet 2 reach bioeconomic equilibrium when the profit functions of both are made equal to zero and solved for E_1 and E_2 as follows:

$$E_{1\text{BE}} = -\frac{c_1 r_1 r_2 - K_1 p_1 q_{11} r_1 r_2 - K_2 p_2 q_{12} r_1 r_2 + E_2 K_2 p_2 q_{12} q_{22} r_1}{K_1 p_1 r_2 q_{11}^2 + K_2 p_2 r_1 q_{12}^2} \qquad (9.87)$$



(a)

(b)

Figure 9.15 Bioeconomic equilibrium, maximum economic yield, and open access effort dynamics of a multispecies fishery.

$$E_{2\mathrm{BE}} = -\frac{c_2 r_2 - K_2 p_2 q_{22} r_2 + E_1 K_2 p_2 q_{12} q_{22}}{K_2 p_2 q_{22}^2} \tag{9.88}$$

In Figure 9.15, we can observe that as effort of the fleet harvesting incidentally the target species of Fleet 2 increases, the effort in bioeconomic equilibrium and maximum economic yield of the other fleet tends to decrease, because both fleets are sharing the stock of Species 2. From this figure, we can observe that as effort of Fleet 2 expands, the open access bioeconomic equilibrium level of effort of Fleet 1 decreases from equilibrium effort level A_1 (for $E_2 = 0$) to A_2. This is so

Table 9.7 Parameter set for the multispecies interdependent fisheries

Parameter	Symbol	Value	Unit of measurement
Carrying capacity – Species 1	K_1	4,000,000	ton
Carrying capacity – Species 2	K_2	2,000,000	ton
Intrinsic growth rate – Species 1	r_1	0.36	1/year
Intrinsic growth rate – Species 2	r_2	0.3	1/year
Catchability coefficient – Fleet 1, Species 1	q_{11}	0.0004	1/vessel/year
Catchability coefficient – Fleet 1, Species 2	q_{12}	0.0002	1/vessel/year
Catchability coefficient – Fleet 2, Species 2	q_{22}	0.0007	1/vessel/year
Price – Species 1	p_1	60	US$/ton
Price – Species 2	p_2	75	US$/ton
Unit cost of effort – Fleet 1	c_1	60,000	US$/vessel/year
Unit cost of effort – Fleet 2	c_2	35,000	US$/vessel/year
Initial biomass – Species 1	$X_{1,0}$	4,000,000	ton
Initial biomass – Species 2	$X_{2,0}$	2,000,000	ton
Exit/entry parameter – Fleet 1	φ_1	2.34279×10^{-6}	vessels/US$
Exit/entry parameter – Fleet 2	φ_2	1.86038×10^{-6}	vessels/US$

because of reductions of Fleet 1 revenues from its incidental harvest of Species 2 increasingly harvested by Fleet 2.

Accordingly, as the effort of Fleet 1 expands, the open access bioeconomic equilibrium level of effort of Fleet 2 also decreases with a relatively greater reduction in the effort level from point B_1 (for $E_1 = 0$) to B_2 (see Figure 9.4b). This is so because Fleet 2 only harvests and obtains revenues from fishing Species 2, which is incidentally harvested by Fleet 1.

The optimum level of effort for each fleet is calculated by making the marginal sustainable revenue equal to their corresponding unit cost of effort (e.g. $\mathrm{MR}_{E1} = \mathrm{MC}_{E1}$). As before, marginal sustainable revenues are estimated by the first derivative of total sustainable revenues for each fleet. The equations for calculating MRE_1 and MRE_2 are the following:

$$\mathrm{MRE}_1 = \frac{K_1 p_1 q_{11} r_2 + K_2 p_2 q_{12} r_2 - 2E_1 K_2 p_2 q_{12}^2 - E_2 K_2 p_2 q_{12} q_{22}}{r_2} - \frac{2E_1 K_1 p_1 q_{11}^2}{r_1} \tag{9.89}$$

$$\mathrm{MRE}_2 = -\frac{K_2 p_2 q_{22}(E_1 q_{12} - r_2 + 2E_2 q_{22})}{r_2} \tag{9.90}$$

The bioeconomic equilibrium and maximum economic yield effort levels for each of the two cases mentioned above obtained with the provided parameter set (Table 9.7) are shown in Figure 9.16.

9.6.2 Effort isoclines: multispecies fishery

In the bioeconomics of isoclines for a fishery where one fleet targets incidentally the target species of another fleet, we obtain isoclines for effort in maximum economic yield and bioeconomic equilibrium. *Effort isoclines* for a fishery are

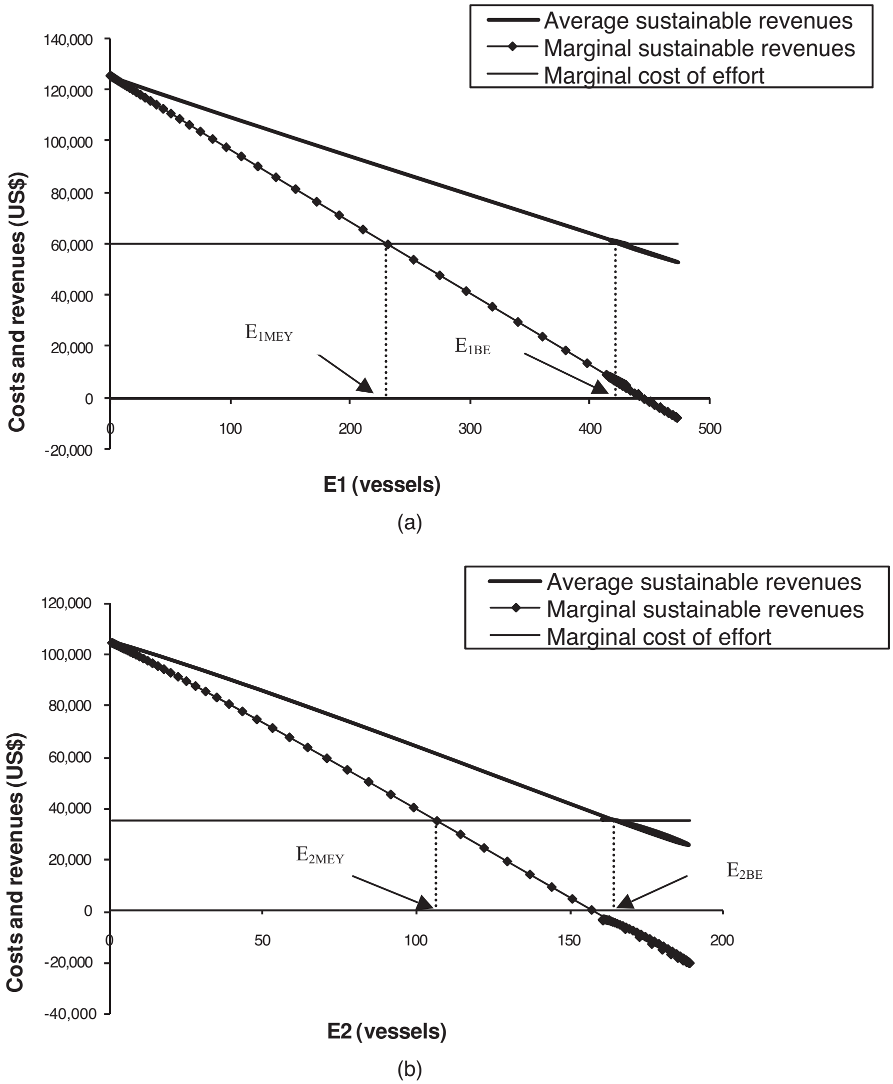


Figure 9.16 Average and marginal sustainable revenues and costs of a multispecies multifleet fishery.

understood as a set of effort levels at which the rate of change, or partial derivative, for one fleet in a pair of interacting fleets, is zero.

By making E_2 equal to zero in Equation 9.85, we obtain an expression for the maximum economic yield isocline for Fleet 1 ($\mathrm{MEYI}_{E1,1}$):

$$\mathrm{MEYI}_{E1,1} = -\frac{c_1 r_1 r_2 - K_1 p_1 q_{11} r_1 r_2 - K_2 p_2 q_{12} r_1 r_2}{2(K_1 p_1 r_2 q_{11}^2 + K_2 p_2 r_1 q_{12}^2)} \tag{9.91}$$

Accordingly, we obtain the maximum economic yield isocline for Fleet 2 ($\mathrm{MEYI}_{E1,2}$) by making the same Equation 9.86 ($E_{1\mathrm{MEY}}$) equal to zero and solving for E_2:

$$\mathrm{MEYI}_{E1,2} = \frac{r_2(K_1 p_1 q_{11} - c_1 + K_2 p_2 q_{12})}{2K_2 p_2 q_{12} q_{22}} \tag{9.92}$$

As before, by making E_1 equal to zero in Equation 9.86 we have the maximum economic yield isocline for Fleet 2 ($\mathrm{MEYI}_{E2,2}$). Again, we obtain the maximum economic yield isocline for Fleet 1 ($\mathrm{MEYI}_{E2,1}$) by making the same Equation 9.86 ($E_{2\mathrm{MEY}}$) equal to zero and solving for E_1:

$$\mathrm{MEYI}_{E2,2} = -\frac{c_2 r_2 - K_2 p_2 q_{22} r_2}{2K_2 p_2 q_{22}^2} \tag{9.93}$$

$$\mathrm{MEYI}_{E2,1} = -\frac{0.5(c_2 r_2 - K_2 p_2 q_{22} r_2)}{K_2 p_2 q_{12} q_{22}} \tag{9.94}$$

Continuing with the same process, the bioeconomic equilibrium isocline for Fleet 1 is obtained by making E_2 equal to zero in Equation 9.87:

$$\mathrm{BEI}_{E1,1} = -\frac{c_1 r_1 r_2 - K_1 p_1 q_{11} r_1 r_2 - K_2 p_2 q_{12} r_1 r_2}{K_1 p_1 r_2 q_{11}^2 + K_2 p_2 r_1 q_{12}^2} \tag{9.95}$$

Accordingly, we obtain the bioeconomic equilibrium isocline for Fleet 2 ($\mathrm{BEI}_{E1,2}$) by making the same Equation 9.87 ($E_{1\mathrm{BE}}$) equal to zero and solving for E_2 as follows:

$$\mathrm{BEI}_{E1,2} = \frac{r_2(K_1 p_1 q_{11} - c_1 + K_2 p_2 q_{12})}{K_2 p_2 q_{12} q_{22}} \tag{9.96}$$

Finally, by making E_1 equal to zero in Equation 9.88 ($E_{2\mathrm{BE}}$), we obtain the bioeconomic equilibrium isocline for Fleet 2 ($\mathrm{BEI}_{E2,2}$). And, by equating to zero expression 9.88 and solving for E_1, we have a bioeconomic equilibrium isocline for Fleet 1 ($\mathrm{BEI}_{E2,1}$):

$$\mathrm{BEI}_{E2,2} = -\frac{c_2 r_2 - K_2 p_2 q_{22} r_2}{K_2 p_2 q_{22}^2} \tag{9.97}$$

$$\mathrm{BEI}_{E2,1} = -\frac{c_2 r_2 - K_2 p_2 q_{22} r_2}{K_2 p_2 q_{12} q_{22}} \tag{9.98}$$

With the BEI and MEYI isoclines calculated above, we can plot them together and have the corresponding joint BE and joint MEY, which provide the effort levels for each fleet of this multispecies multifleet fishery (Figure 9.17).

The effort values for Fleets 1 and 2 resulting from the joint BE of Figure 9.17 correspond to the bioeconomic equilibrium effort values shown in Figure 9.14 in the intersection of PEC and EEC curves for E_1 and E_2 and in points A_2 and B_2 of Figure 9.15. The joint MEY effort values of Figure 9.16 correspond to the ones obtained by applying the principle of marginal costs of effort equal to marginal revenues of effort for each of the two fleets. We can also observe from Figure 9.17 the open access effort trajectory converging to the joint BE of E_1 and E_2.

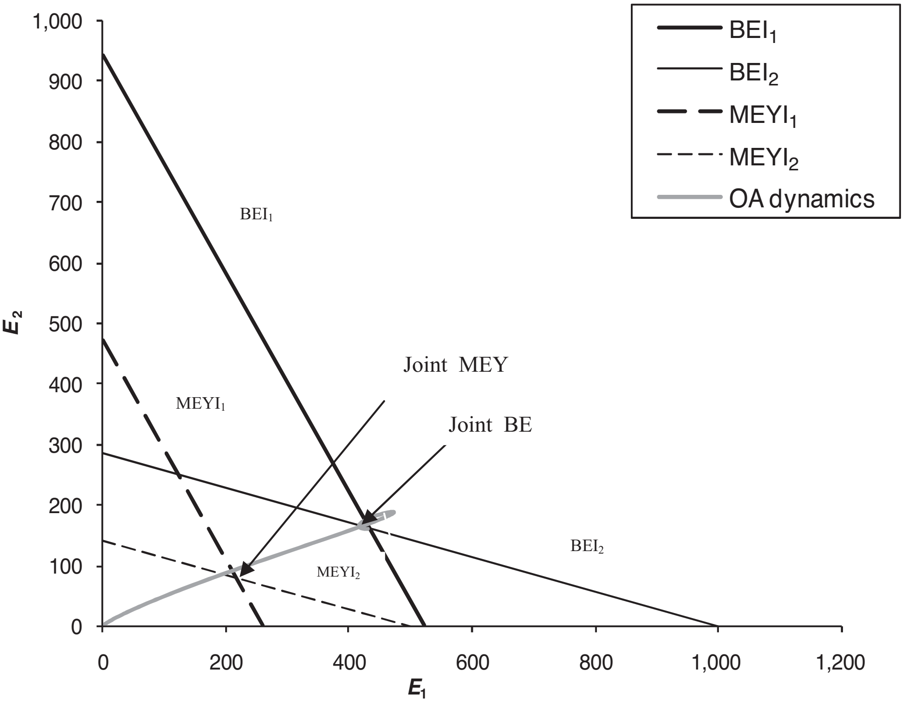


Figure 9.17 Bioeconomic isoclines: joint MEY and joint BE.

9.7 Case 5: sequential technological interdependencies of small-scale and industrial fleets – an age-structured model

In sequential fisheries, where two fleets (e.g., small-scale and industrial vessels) allocate their fishing intensity in spatially different areas, there are usually technological as well as biological interdependencies, because harvesting different components of the population structure take place. This type of situations is relevant to most shrimp (*Pennaeus* spp.) fisheries of the world. It is also the case of many grouper (*Epinephelus* spp.) fisheries where juveniles and young adults distribute nearby coastal areas and adults occur in isobaths of deeper waters.

Small-scale boats tend to allocate their effort in estuaries, costal lagoons, and nearby coastal areas where juveniles and, in some cases, young adults inhabit. As a result, the length frequency of the harvest of these small-scale boats is represented by individuals of the early ages of their life cycle. In Figure 9.18, this type of boats harvest, for instance, individuals of ages 2–5, as indicated in black in the age-specific frequency distribution.

The bioeconomics of sequential fisheries have been discussed under equilibrium conditions by Charles and Reed (1985) and Willmann and Garcia (1985). Bioeconomic models have also been built to determine the optimal allocation of quotas between two fleets that sequentially fish on a single stock (Geen and Nayar, 1988).

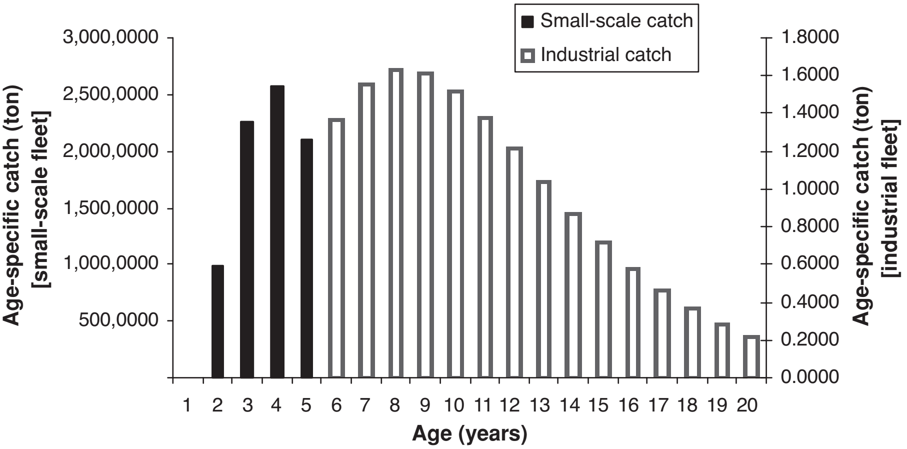


Figure 9.18 Length frequency distribution of harvest of small-scale and industrial fleets.

9.8 An age-structured sequential bioeconomic model

To explore management questions in fisheries where small-scale and industrial fleets affect different components of the population structure, it is necessary to expand both the population age-structure Equation 5.21 and the age-specific catch Equation 5.22 from Chapter 5 to include an additional effort with the corresponding age-specific catchability coefficients. This is necessary to account for the age-specific fishing mortalities ($F_{1,i,t} = E_{1,t}q_{1,i}$ and $F_{2,i,t} = E_{2,t}q_{2,i}$) caused by heterogeneous fleets that spatially allocate their effort in areas where demersal resources spatially segregate themselves according to their maturity, as expressed in Equations 9.99, 9.100, and 9.101.

$$N_{i+1,t+1} = N_{i,t}e^{(-(F_{1,i,t}+F_{2,i,t}+M))} \tag{9.99}$$

$$Y_{1,i,t} = N_{i,t}W_i\left(\frac{F_{1,i,t}}{F_{1,i,t}+F_{2,i,t}+M}\right)(1-e^{(-(F_{1,i,t}+F_{2,i,t}+M))}) \tag{9.100}$$

$$Y_{2,i,t} = N_{i,t}W_i(\frac{F_{2,i,t}}{F_{1,i,t}+F_{2,i,t}+M})(1-e^{(-(F_{1,i,t}+F_{2,i,t}+M))}) \tag{9.101}$$

Profits for each of the fleets over time are calculated as before by adding up the product of the age-specific catch and price, minus the corresponding total cost of effort per fleet type.

The age-specific catchability coefficients of each fleet m are estimated in the model by the Baranov (1918) area swept method as follows:

$$q_{m,i} = -\left\{\ln\left[1-\left(c\frac{a}{\text{Area}}\right)SEL_{m,i}\right]\right\} \tag{9.102}$$

where a is the area swept per day (km^2), Area is the area of stock distribution (km^2), and c is the probability of capture.

Table 9.8 Parameter set for the age-structured bioeconomic model for the sequential fishery

Parameter	Symbol	Value	Units
Natural mortality	M	0.21	1/year
Recruitment	R	25,000,000	1/year
Fishing mortality	F	0.18	1/year
Maximum length	L^{∞}	92	cm
Growth	k	0.18	1/year
Parameter of length–weight relationship	a	0.013	g
Parameter of length–weight relationship	b	3.0546	g
Price of species	P	5,000	US$/ton
Unit cost of effort – industrial fleet	c_1	45,000	US$/vessel/year
Unit cost of effort – small-scale fleet	c_2	4,800	US$/vessel/year
Exit/entry parameter – industrial fleet	ϕ_1	0.000005	vessels/US$
Exit/entry parameter – small scale fleet	ϕ_2	0.00005	vessels/US$
Area swept – industrial vessel	a_1	1.5	km^2/vessel/year
Area swept – small scale vessel	a_2	0.8	km^2/vessel/year
Area of resource distribution	area	7,600	km^2
Length at 50% gear retention – industrial	$L_{50\%,1}$	45	cm
Length at 50% gear retention – small scale	$L_{50\%,2}$	28	cm
Length at 75% gear retention – industrial	$L_{75\%,1}$	65	cm
Length at 75% gear retention – small scale	$L_{75\%,2}$	39	cm
Parameter selectivity equation – industrial	S_{1i}	2.47	–
Parameter selectivity equation – small scale	S_{1a}	2.80	–
Parameter selectivity equation – industrial	S_{2i}	0.05	–
Parameter selectivity equation – small scale	S_{2a}	0.10	–
Probability of capture	c	0.90	–
Beverton–Holt recruitment parameter	α	25,000,000	individuals
Beverton–Holt recruitment parameter	β	25,000	–

The age-specific selectivity of the gear, $\mathrm{SEL}_{m,i}$, can be expressed by the following equation:

$$\mathrm{SEL}_{m,i} = \frac{1}{1 + \mathrm{e}^{(s_1 - s_2 L)}} \tag{9.103}$$

where

$$s_1 = L_{50\%}\left(\frac{\ln 3}{L_{75\%} - L_{50\%}}\right)$$

$$s_2 = \frac{s_1}{L_{50\%}}$$

$L_{50\%}$ = length at 50% gear retention
$L_{75\%}$ = length at 75% gear retention.

In Table 9.8, parameters are provided to estimate age-specific catchability using the Baranov area swept method and the logistic gear selectivity function expressed below.

To illustrate the sequential performance of this type of fishery, in Figure 9.19 we have the evolution of effort of the two fleets harvesting different components

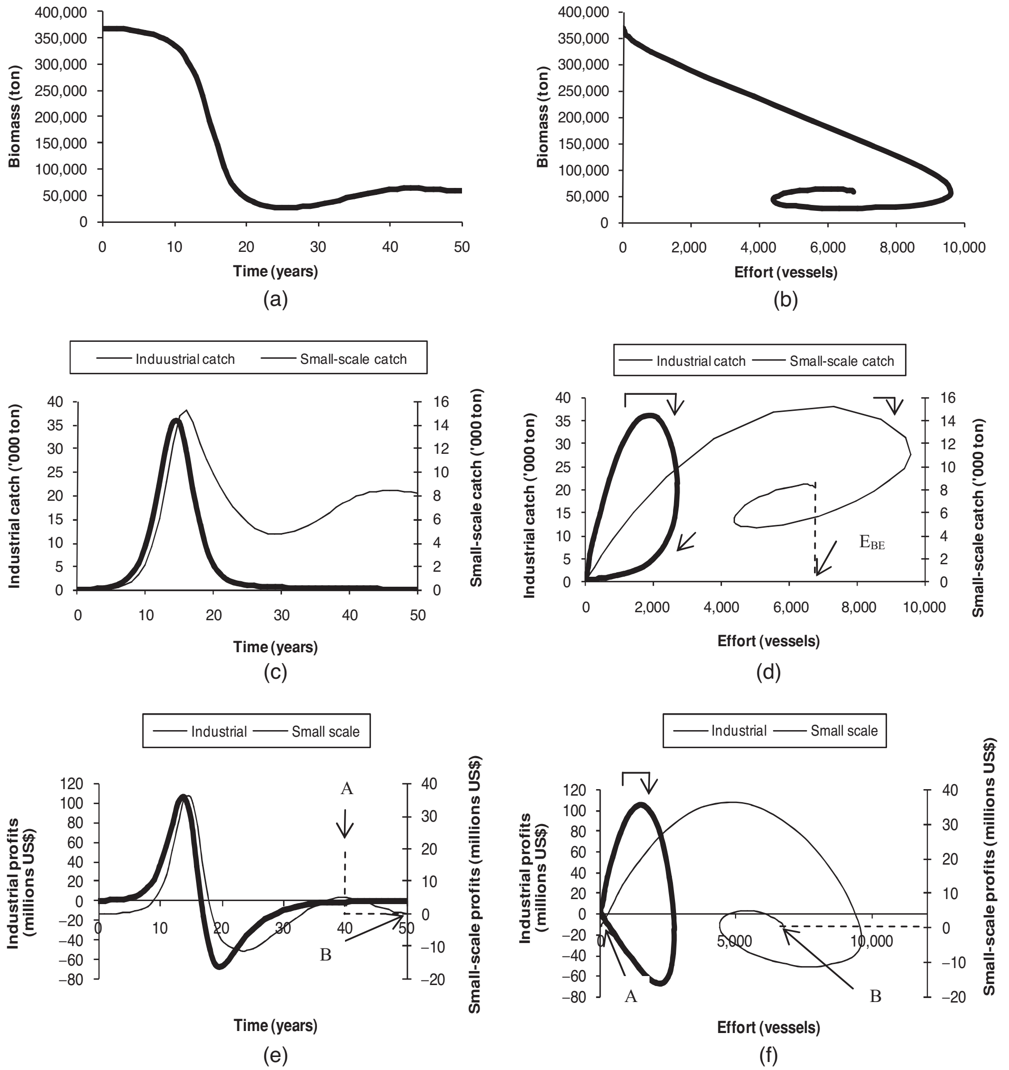


Figure 9.19 Dynamics of biomass, harvest, and profits of small-scale and industrial fleets harvesting different components of the population structure.

of the population structure. In this case, like in many parts of the tropical world, in the long run small-scale fleets tend to exclude industrial fleets that require higher levels of stock abundance to pay for their unit cost of effort.

We can see from Figure 9.19 that under open access, biomass can be driven to very low levels because not only spawners are harvested by an industrial fleet but also juveniles are subject to exploitation by small-scale vessels. After point A (Figures 9.19e and 9.19f), the industrial fleet is excluded from the fishery and small-scale boats increase the effort to harvest the biomass released when fishing mortality of the industrial fleet becomes zero ($F_1 = 0$). At the end, under open

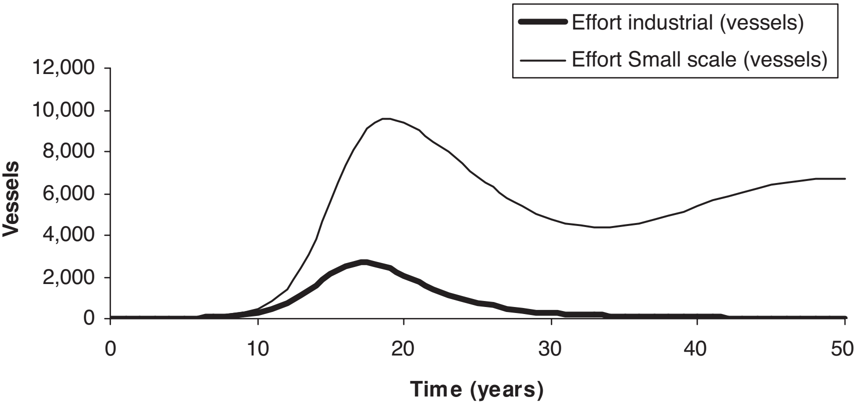


Figure 9.20 Open access fleet dynamics of both small-scale and industrial vessels.

access, the small-scale fleet reaches bioeconomic equilibrium when the profits of these vessels become zero. This can be seen in point B of Figures 9.19e, 9.19f, and 9.20.

In Figure 9.20, we can see the dynamics of this sequential fishery whereby small-scale fleet excludes in the long run the industrial fleet (see point A of Figure 9.19). As mentioned before, this occurs because the economic equilibrium level of biomass for the industrial fleet is higher than the one for the small-scale fleet, which has a lower unit cost of effort and can operate at lower levels of stock biomass.

With this model, one can estimate the sequential externalities (positive or negative) involved in the exit–entry process of the different fleets affecting either juveniles or adults.

The parameter set for the sequential fishery illustrated above is included in Table 9.8. It should be pointed out that this multifleet, age-structured model was developed using a Beverton–Holt recruitment function. As shown in Chapter 5, different recruitment functions could be used to represent the relationship of the spawning stock and recruitment of postlarvae for specific species. In Chapter 12, the uncertainty inherent in recruitment processes of marine fisheries will be included through spawner-recruit functions with stochastic elements built in.

A number of management regulations affecting size composition of the catch and/or area closures can be explored to estimate the effect on spawning stock biomass, harvest, and rent of a fishery with clear segregation of juveniles and adults over space and time. This last model is a transition to more complex spatial bioeconomic analysis, which will be discussed in Chapter 10.

Input and output regulations discussed in Chapter 7 can be explored to manage fisheries with ecological and/or technological interdependencies. Access rights to multispecies fisheries can also be explored, as suggested by Squires *et al.*, 1998.

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Chapter 10

Spatial management of fisheries

In Chapter 9, we began the transition from the dynamic pool assumption of homogeneous resource distribution over space to the simplest spatial segregation of stocks (i.e., juveniles found in estuaries and nearby coastal areas and adults inhabiting deeper waters) harvested in sequential fisheries. This spatial characteristic was included through the age-specific catchability coefficient of fleets harvesting different components of the population structure without explicit spatial variables in the bioeconomic model.

This chapter reviews the need for understanding the spatial heterogeneity in marine resource abundance and the corresponding spatial behavior of fishing intensity over time. The recognition of the implications of dynamic pool assumptions in overestimating stock abundance is discussed together with spatial modeling efforts aimed at relaxing this unrealistic assumption for sedentary species and many low-mobility demersal resources. Responsible spatial management and modeling of fisheries require understanding the spatial behavior of species with the corresponding abundance heterogeneity in space and time and the ecological interdependencies within an ecosystem framework. It also involves proper understanding of fisher behavior driving the spatial allocation of fishing intensity. This last aspect is fundamental to fisheries economics which focuses on the motivation of fishermen in their fishing behavior over space and time.

The Schaefer–Gordon and Beverton–Holt models discussed in previous chapters laid the foundations for incorporating spatial considerations into population dynamics, but in the 1950s were unable to follow up their ideas due to the inadequacy of computational facilities. In general, these models are based on dynamic pool assumptions, which establish that (1) the resource is homogeneously distributed in space; (2) ages are perfectly mixed; and either (3) fishing effort is applied uniformly over the range of resource distribution, or (4) after fishing effort has been applied, the resource is able to redistribute itself according to (1) and (2). Not surprisingly, for sedentary and low-mobility resources, models based on dynamic pool assumptions are inadequate and result in serious model error. Local habitats are unequal in quality and holding capacity throughout the stock range. The spatial distribution of these resources is patchy, in terms of size, density, and age structure. As a result, fishing intensity is spatially heterogeneous. The principal consequence of this spatial heterogeneity is that under dynamic pool assumptions, the productive potential of the stock is overestimated, increasing the risk of overexploitation and collapse of the fishery.

In this chapter, we will begin by relaxing the assumption of homogeneous recruitment distribution over space, common to dynamic pool models. We will do that by spatially distributing recruits over space and time. The next question is: How do we emulate the heterogeneity in recruitment distribution over space with the possibility of having zero recruits in areas that are assumed nonsuitable for population recruitment success. This will be done by using the negative binomial distribution that allows for zero values and therefore reflect properly this spatial aspect of recruitment of new individuals over space.

Two general situations are explored in this chapter: (1) a spatially distributed population of a single stock and (2) fisheries of metapopulations where sources are distinguished from sinks. To explore these complexities and possible effects of alternative spatial management strategies, simulation experiments can be carried out through the use of spatial bioeconomic models designed to answer relevant management questions.

We will present mathematical expressions and show them explicitly in tables with spatial format to represent how individuals of different ages survive and grow over time in every site of the geographical area where recruitment can successfully take place. We can then calculate age-specific biomass over space and time.

Once we have the spatial resource dynamic built in, we can then represent the spatial behavior of fishers in response to heterogeneous resource abundance in space and time and the corresponding operating costs and revenues of fishing in alternative sites when departing from a specific port. With the quasi rent of the variable costs over space and time, the spatial distribution of fishing intensity will be calculated and the long-run dynamics of effort will be determined with the spatially adapted Vernon Smith (1969) function.

With the spatial resource distribution and corresponding fishing behavior over space, we will proceed to show the following:

1. The open access dynamics of fishery targeting a low-mobility sedentary species represented over time and space
2. The numerical equilibrium biomass, yield, and profits over space
3. The minimum site-specific catch per unit of effort needed for vessels to fish in site s located at a distance D_s from port of origin
4. The open access effect of distance on the trajectories of heterogeneous catch per unit of effort of different fishing sites over time ($\mathrm{CPUE}_{s,t}$)
5. The open access effect on the heterogeneous site-specific $\mathrm{CPUE}_{s,t}$ of vessels fishing in different sites located at the same distance from port of origin
6. The trajectory of quasi profits of the variable costs of fishing in site s over time under open access
7. The bioeconomic effects of spatial management strategies like marine-protected areas (MPAs)

10.1 Spatially distributed population of a single stock

10.1.1 Heterogeneous recruitment density in space and time

The first aspect that we need to modify from the age-structured model we discussed in Chapter 5 is that once we select the appropriate recruitment function and estimate the number of recruits over time, we proceed to distribute them over space.

In Chapter 5, we disaggregated resource population and harvest by age cohorts that changed over time. In this chapter, we relax the assumption of homogeneous resource distribution over space and proceed to spatially distribute recruits over time.

10.1.1.1 Recruitment

The heterogeneous distribution of recruits over space can be modeled by multiplying the estimated number of recruits produced by the spawning stock (SS_t) over time $R_{t+1} = f(\mathrm{SS}_t)$ (e.g., estimated using Ricker, Beverton–Holt, or stochastic recruitment functions) by a probability density function that distributes them over space.

In this chapter, a spatially adapted Beverton–Holt (1957) stock-recruitment function was multiplied by a negative binomial distribution that allows for patches of zero recruitment to generate a heterogeneous recruitment density over time. The negative binomial distribution (e.g., Elliot, 1977; Welch and Ishida, 1993; Seijo *et al.*, 2004) can be used to represent spatial heterogeneity in recruitment densities as follows:

$$P(d) = \left(1 + \frac{\mu}{\varepsilon}\right)^{-\gamma} \frac{(\varepsilon + d - 1)!}{d!(\varepsilon - 1)!} \left(\frac{\mu}{\mu + \varepsilon}\right)^{d} \qquad (10.1)$$

where d represents recruitment density, ε is the family member of the negative binomial, and μ is the mean recruitment density. Each fishing site s can be assigned a specific geographical position or latitude/longitude.

For a given maximum number of annual recruits, the number of individuals settling at geographic coordinates of site s in year t is estimated by Equation 10.2 as follows (Seijo *et al.*, 2004):

$$R_{s,t} = \frac{\sum_s \mathrm{SSB}_{s,t}\alpha}{\beta + \sum_s \mathrm{SSB}_{s,t}} P(s, d) \qquad (10.2)$$

where $\sum_s \mathrm{SSB}_{s,t}$ is the total *spawning* biomass over time. $\mathrm{SSB}_{s,t} = \sum_{i=sm}^{\lambda} X_i$, α is the maximum annual recruitment, and sm is the age at sexual maturity. β is total spawning biomass for $\alpha/2$. In this case, as indicated above, $P(s, d)$ is the negative binomial probability density function. Therefore, it is used here to distribute recruits density d over space s [i.e., site s with specific geographic coordinates of latitude (k) and longitude (l)] and time t.

Figure 10.1 shows the spatial distribution of recruits in patches of heterogeneous density. With spatial heterogeneity of resource distribution, we can now

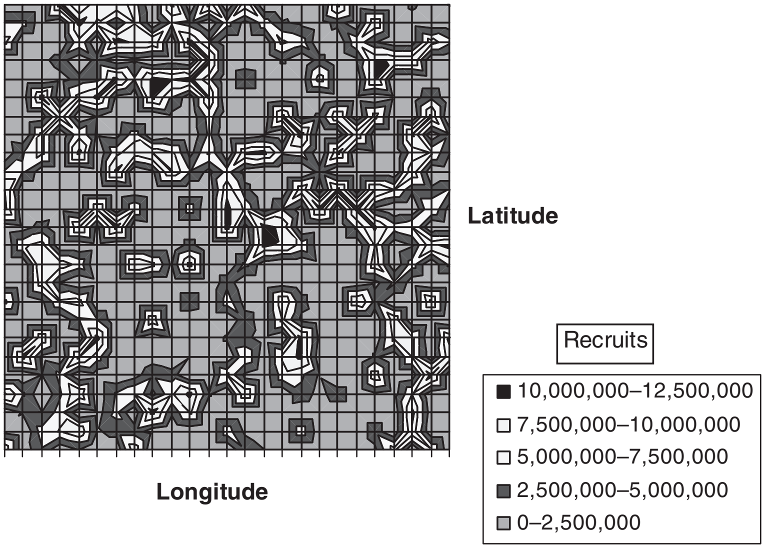


Figure 10.1 Spatial distribution of recruits using a negative binomial function for recruits settlement over space.

have a model with age-specific matrices of population and biomass distributed over space.

10.1.1.2 Dynamics of the population structure over space

To estimate the dynamics of the population over space, it is fundamental to be able to follow changes in the number of individuals in each cohort in every geographic cell during the relevant time period (i.e., year, month, or week, depending on the life cycle of the aquatic species). When fishing and natural mortality are continuous, the basic assumption is that the survival of cohort i for alternative site s is given by:

$$\frac{dN_{i,s}}{dt} = -(F_{i,s,t} + M)N_{i,s,t} \tag{10.3}$$

where $N_{i,s,t}$ is the number of individuals of age i in site s in time t. $F_{i,s,t}$ is the age-specific fishing mortality over space and time and M represents the instantaneous natural mortality rate. An estimation of stock size is needed as an input in order to initialize the spatial bioeconomic model in time $t = 0$.

Solving Equation 10.3 for the number of individuals in the cohort surviving during the time period in geographic site s, we have:

$$N_{s,i+1,t+1} = N_{s,i,t}e^{[-(M+F_{s,i,t})]} \tag{10.4}$$

Age-specific fishing mortality over space is calculated by multiplying site-specific effort ($E_{s,t}$) by the age-specific catchability (q_i), $F_{i,s,t} = E_{s,t}q_i$.

Using the area swept method (Sparre *et al.*, 1989) appropriate for low mobility and sedentary species, and a simple logistic selectivity function, we can calculate q_i as follows:

$$q_i = -\ln\left[1 - \left(\frac{a\,\mathrm{SEL}_i\,c}{\mathrm{Area}}\right)\right] \tag{10.5}$$

where a is area swept per day in km^2, Area is area of stock distribution in km^2, and c is probability of capture.

The age-specific selectivity of the gear, SEL_i, can be expressed by the following equation (Sparre and Willman, 1993):

$$SEL_i = \frac{1}{1 + e^{s_1 - s_2 \cdot L_i}} \tag{10.6}$$

where:

$$s_1 = L_{50\%} \ln\left(\frac{3}{L_{75\%} - L_{50\%}}\right)$$

and

$$s_2 = \frac{s_1}{L_{50\%}}$$

$L_{50\%}$ = length at 50% gear retention
$L_{75\%}$ = length at 75% gear retention

In Table 10.1 we can observe that individuals of the same age (age 1 in this matrix) are distributed over space in a grid that could have geographic coordinates attached to it. Every cell (m, n) constitutes a specific site s in the area of resource distribution so we have individuals of age i located, for instance, in cell 3,2 ($N_{i,32}$).

For population over space, we will have as many matrices as the maximum age of species (from $i = 1$ to longevity) like the one in Table 10.1.

In each age-specific population matrix, the number of individuals in every consecutive age will change in each site of the stock distribution as a function of the survival rate of individuals from the previous age.

Table 10.1 Population over space *m, n*: matrices of individuals age 1 to maximum age.

m, n	**1**	**2**	**3**	. . .	***n***
1	$N_{i,11}$	$N_{i,12}$	$N_{i,13}$	. . .	$N_{i,1n}$
2	$N_{i,21}$	$N_{i,22}$	$N_{i,23}$	. . .	$N_{i,2n}$
3	$N_{i,31}$	$N_{i,32}$	$N_{i,33}$	. . .	$N_{i,3n}$
. . .	. . .	. . .	. . .	. . .	. . .
m	$N_{i,m1}$	$N_{i,m2}$	$N_{i,m3}$	. . .	$N_{i,mn}$

Table 10.2 Age-specific biomass over space.

m, n	**1**	**2**	**3**	...	***n***
1	$X_{i,11}$	$X_{i,12}$	$X_{i,13}$	...	$X_{i,1n}$
2	$X_{i,21}$	$X_{i,22}$	$X_{i,23}$	...	$X_{i,2n}$
3	$X_{i,31}$	$X_{i,32}$	$X_{i,33}$	...	$X_{i,3n}$
...	...	...	...	...	...
m	$X_{i,m1}$	$X_{i,m2}$	$X_{i,m3}$	...	$X_{i,mn}$

As discussed in Chapter 5, the biomass available in each site is calculated by Equation 10.7 as follows:

$$X_{s,t} = \sum_{i=1}^{i=k} N_{i,s,t} W_i \tag{10.7}$$

The age-specific spatial distribution of biomass is shown in Table 10.2. Again, we will have k biomass matrices and an aggregate matrix that sums up all the biomasses of different ages located in site s. Population biomass over time is then: $X_t = \sum_s X_{s,t}$.

Once we have calculated available biomass in each fishing site over time, we can then determine the costs of steaming and fishing in alternative fishing grounds of resource distribution. To do so, we first obtain the distances between the port of origin and every geographic cell of the stock area.

10.2 Distance from port to alternative fishing sites

To estimate distance from fishing port to alternative sites, each cell is specified a width and length. The distances to fishing sites from alternative locations of fishing port were estimated using the following equation:

$$D_S = \sqrt{[\mathrm{LC}(y-m)]^2 + [\mathrm{WC}(z-n)]^2} \tag{10.8}$$

where:

LC = length of cell
WC = width of cell
$m = 1, 2, 3, \ldots, \mathrm{RG}$; RG = rows of grid
$n = 1, 2, 3, \ldots, \mathrm{CG}$; CG = columns of grid
$y = \mathrm{RG}/2$
$z = \mathrm{CG}/2$

Each site s corresponds to a cell with specific row and column or longitude and latitude.

Distance isolines from port A to different geographic cells of resource distribution are presented in Figure 10.2 with ranges (1 through 5) up to 100 km.

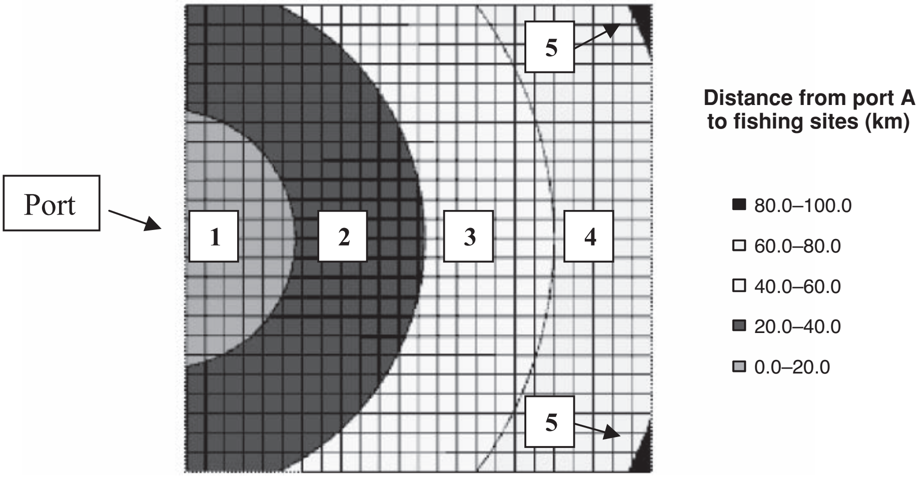


Figure 10.2 Distance to fishing sites from port of origin.

With the calculated distances from port, D_s, we can then proceed to represent the spatial behavior of fishers over time.

10.3 Spatial fishing behavior

As mentioned before, fishermen behavior is the focus of fisheries economics. The dynamic behavior of both the resource and the fishermen is the focus of fisheries bioeconomics. Modeling the spatial dynamics of marine fisheries allows for better understanding the intertemporal behavior of fishing intensity over space and thus to develop adequate management strategies.

Some spatial fisher behavior strategies documented in the literature include the following:

1. Proportional distribution according to the spatial abundance of the resource (Caddy, 1975)
2. Sequential distribution to those patches of greatest abundance (Hilborn and Walters, 1987)
3. Random search (Hilborn and Walters, 1992)
4. Free distribution of fishing intensity (Gillis *et al.*, 1993)
5. Proportional distribution to (Seijo *et al.*, 1994, 1998):
    - The quasi rent of the variable costs (including transfer costs of traveling from port to alternative fishing sites)
    - The friction of distance, i.e., nonmonetary costs associated to vessel distance traveled to fishing sites
    - The probability of finding the target species in profitable levels at alternative sites

In Appendix 1, the reader can find fishery performance under three alternative spatial behaviors of fishing intensity. Other possible spatial fisher behavior strategies for sedentary or low-mobility species can also be explored. It will depend not only on the heterogeneity of resource distribution in space and time but also on vessel autonomy, searching capacity, and the corresponding fishing technology.

For highly mobile pelagic resources, their migratory behavior and dynamic changes in environmental variables, such as water temperature and food availability (spatial distribution of prey), become relevant factors for devising spatial fisher behavior strategies.

The spatial behavior of fishing intensity (effort per unit area) over time, $E_{s,t}$, is obtained by the following equation:

$$E_{s,t+1} = \frac{\text{quasi}\,\pi_{s,t}}{\sum_s \text{quasi}\,\pi_{s,t}} V_{t+1}\,\text{fd} \tag{10.9}$$

where fd are the average number of fishing days per vessel per year and, $quasi\pi_{s,t}$ are the quasi profits of the variable costs of a vessel from port A fishing in site s, calculated as follows:

$$\text{quasi}\,\pi_{s,t} = py_{st} - C_{st}E_{st} \tag{10.10}$$

The variable costs per day of vessels fishing in site s over time (C_{st}) are estimated by (adapted from Anderson, 2002):

$$C_{st} = \frac{\frac{D_s}{v}c_1 + (L - \frac{D_s}{v})c_2}{L} \tag{10.11}$$

where D_s is round trip distance between port of origin and fishing site s (km), v is steaming speed of vessels (km/day), c_1 is cost per day of operating a vessel when steaming (\$/day), c_2 is cost per day of operating a vessel when fishing (\$/day), and L is average length of trip in days.

From Equation 10.11, we have two variable costs associated to the spatial behavior of fishing intensity: the costs of steaming $\frac{D_s}{v}c_1$ to the fishing site and the cost of fishing $(L - \frac{D_s}{v})c_2$.

Table 10.3 shows the matrices of quasi profits of variable costs over space in time t, determining spatial behavior of fishing intensity in time $t + 1$.

The number of vessels over time active in the fishery (V_t) is calculated by numerically integrating (using Euler numerical integration with DT = 1, in this case) the spatially adapted Vernon Smith function, as follows:

$$V_{t+1} = V_t + \phi\left[\sum_s (pY_{st} - C_{st}) - \text{FC}\,V_t\right] \tag{10.12}$$

Table 10.3 Spatial behavior of fishing intensity over time. (a) Quasi-rent of variable costs in time t. (b) Fishing intensity over space in time $t+1$.

m, n	**1**	**2**	**3**	**…**	**n**
1	$q\pi_{i,11}$	$q\pi_{i,12}$	$q\pi_{i,13}$	$\cdots$	$q\pi_{i,1n}$
2	$q\pi_{i,21}$	$q\pi_{i,22}$	$q\pi_{i,23}$	$\cdots$	$q\pi_{i,2n}$
3	$q\pi_{i,31}$	$q\pi_{i,32}$	$q\pi_{i,33}$	$\cdots$	$q\pi_{i,3n}$
…	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
m	$q\pi_{i,m1}$	$q\pi_{i,m2}$	$q\pi_{i,m3}$	$\cdots$	$q\pi_{i,mn}$

→

m, n	**1**	**2**	**3**	**…**	**n**
1	$E_{i,11}$	$E_{i,12}$	$E_{i,13}$	$\cdots$	$E_{i,1n}$
2	$E_{i,21}$	$E_{i,22}$	$E_{i,23}$	$\cdots$	$E_{i,2n}$
3	$E_{i,31}$	$E_{i,32}$	$E_{i,33}$	$\cdots$	$E_{i,3n}$
…	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
m	$E_{i,m1}$	$E_{i,m2}$	$E_{i,m3}$	$\cdots$	$E_{i,mn}$

As before, FC are the annual fixed costs of a vessel. Yield from site s, in time period t, is given by the following spatially specified age-specific catch equation:

$$y_{st} = \sum_i X_{ist} \left[\frac{F_{ist}}{F_{ist} + M} (1 - e^{[-(F_{ist}+M)]}) \right] \tag{10.13}$$

An Excel® program was developed to conduct spatial management simulations with the mathematical model described above. Bioeconomic parameters used are presented in Table 10.4.

The temporal distribution of biomass, yield, and rent aggregated over space, shown in Figure 10.3, exhibits the same pattern of the ones presented in Chapters 2 and 5 when discussing the dynamic Shaefer–Gordon and Beverton–Holt models. The analysis assumes that the population is at unfished equilibrium at the start of the first year of the simulation.

We can observe from Figure 10.3 that the distribution of biomass, yield, and rent over space responds to the location of the port and the spatial fishing intensity strategy (in this case, proportional to quasi profits of variable costs). So the transition is from spatially disaggregated biomass, and corresponding yield and profits over space, to aggregated performance values over time.

10.3.1 Minimum catch per unit of effort over space

One important implication of conducting spatial analysis of fisheries is being able to determine what is the minimum site-specific catch per unit of effort (CPUEmin_s) that will be necessary for a vessel to cover its variable costs considering both steaming and fishing costs. It is determined by:

$$\text{CPUE}\min_s = \frac{\left[\dfrac{\frac{D_s}{v} c_1 + (L - \frac{D_s}{v}) c_2}{L} \right]}{p} \tag{10.14}$$

The dynamic catch per unit of effort ($\text{CPUE}_{s,t}$) at different sites is then estimated by adding over all ages the product of age-specific catchability coefficient

Table 10.4 Bioeconomic parameters for a scallop fishery.

Parameter	Symbol	Value	Units
Maximum age of species	λ	10	years
Age at first maturity	sm	4	years
Natural mortality coefficient	M	0.33	1/year
Parameter k of V.B growth equation	k	0.38	1/year
Parameter t_0 of V.B growth equation	T_0	0.5	1/year
Maximum length of species	L_∞	14.54	cm
Maximum weight of species	W_∞	46.6	g
Parameter alpha of B-H recruitment	α	3,000,000,000	recruits
Parameter beta of B-H recruitment	β	30,301	ton
$L_{50\%}$ gear retention	$L_{50\%}$	7.5	cm
$L_{75\%}$ gear retention	$L_{75\%}$	10.5	cm
Area swept per day	a	0.728	km^2
Total area of resource distribution	area	1,800	km^2
Probability of capture	c	0.9	–
Length of trip	L	5	days
Steaming speed of vessel	v	50	Km/day
Operating cost of vessel steaming	C_1	250	\$/day
Operating cost of vessel fishing	C_2	50	\$/day
Fixed cost	FC	2,000	US\$/vessel/year
Friction of distance parameter	φ	0	–
Price of species	p	10,000	US\$/ton
Exit–entry parameter	ϕ	0.000055	Vessels/US\$
Initial number of vessels	V_0	1	vessel
Average number of fishing days	FD	150	days/vessel/year
Parameter, neg. bin. distribution	ε	15	–
Parameter, neg. bin. distribution	μ	5	–

and biomass of individuals of the different ages at each geographic cell. The spatial $\text{CPUE}_{s,t}$ is then expressed in Equation 10.15 as follows:

$$\text{CPUE}_{s,t} = \sum_i (q_i X_{ist}) \tag{10.15}$$

The total catch per unit of effort (TCPUE_t) is then estimated by adding $\text{CPUE}_{s,t}$ over the space of resource densities.

To represent the spatial bioeconomic dynamic just described, two situations are distinguished and discussed below: (1) spatial fishing behavior over time considering same initial biomass available in fishing sites located at different distances from port of origin and (2) spatial fishing behavior considering different initial local biomasses available in fishing sites located at the same distance from port of origin.

In Figure 10.4, the trajectory of patch-specific biomass and corresponding catch per unit of effort in three of the 625 geographic cells built in this spatial model is shown. The fishing site located in the nearest geographical position (site 1 at 15 km from port) will continue to be fished out as long as $\text{CPUE}_{s,t} >$ CPUE min_s. The same occurs with fishing sites 2 and 3 that are located at greater distances from port and require higher CPUEmin_s to operate.

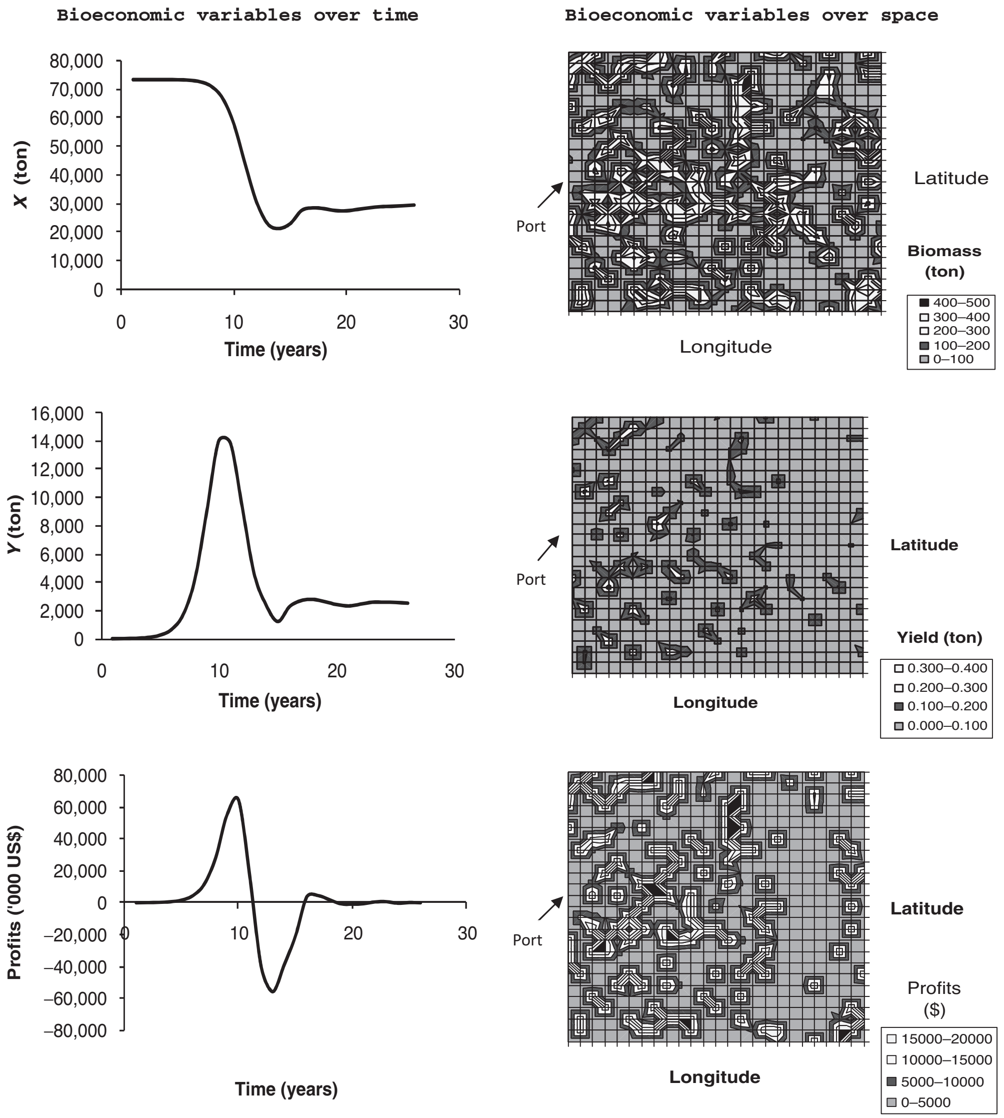


Figure 10.3 Bioeconomic performance variables over space and time.

Once the CPUE falls below its corresponding CPUEmin needed to cover the variable costs of fishing in the specific site, fishing intensity in that location will drop to zero (see point A in Figure 10.4b) and remain there until site-specific biomass (Figure 10.4a) recovers to the level at which quasi profits of the variable costs are greater than zero, and hence fishing intensity occurs in this site. For the closest site located at 15 km, we can see that fishing intensity occurs just above the minimum CPUE to fish at 15 km of distance (Figure 10.4 point B).

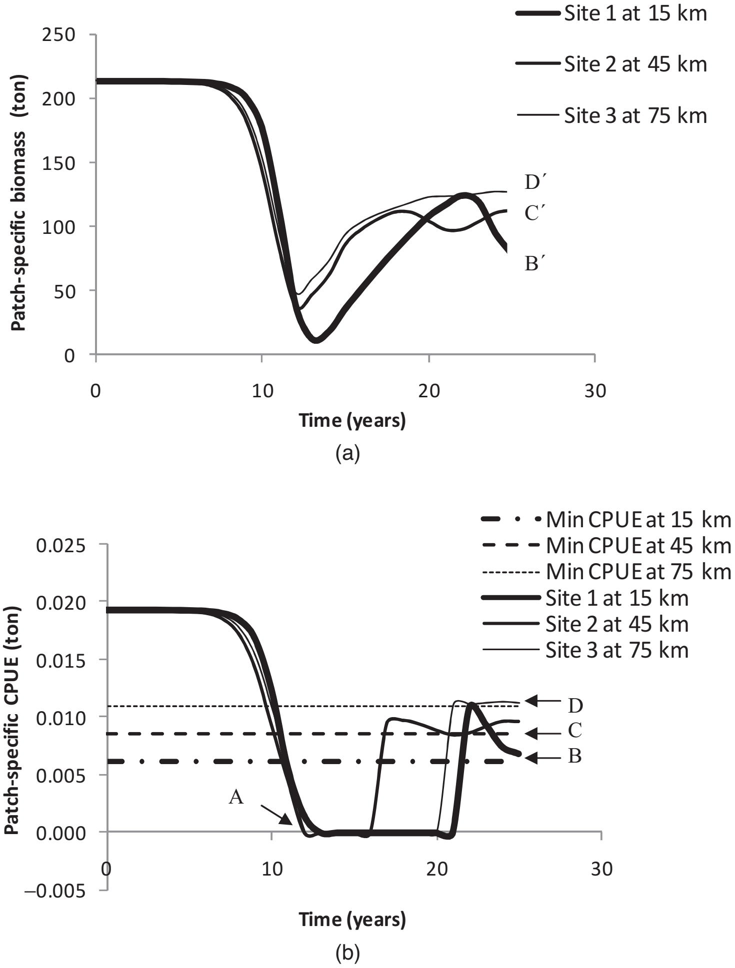
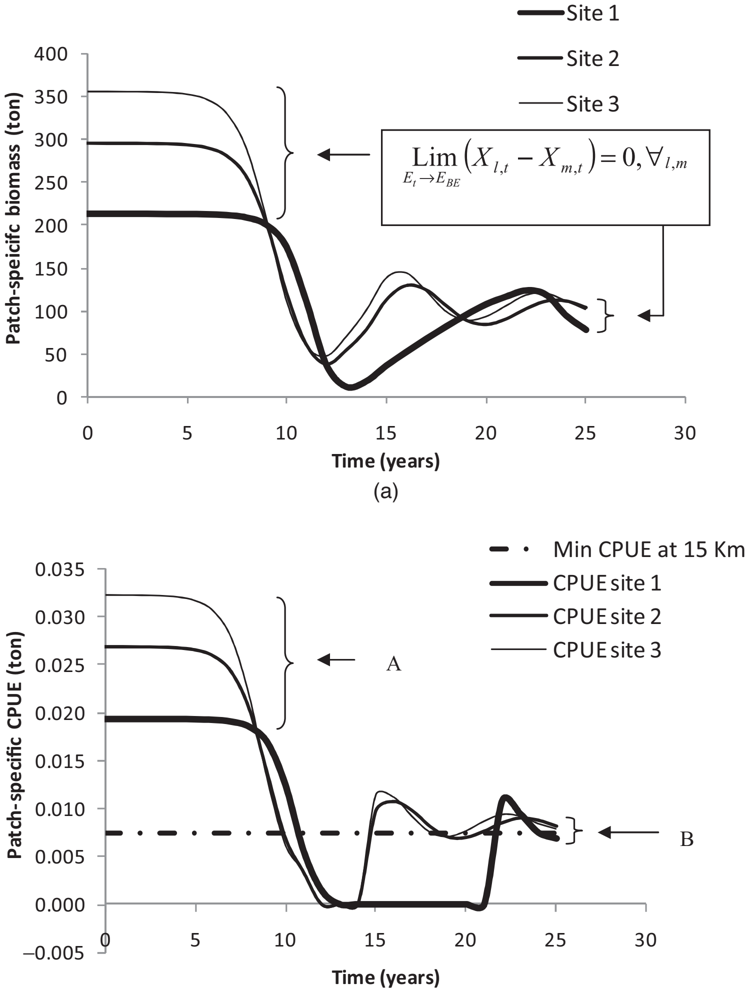


Figure 10.4 Site-specific biomass and CPUE over time located at different distances from port.

For fishing site 2, we can see that there is fishing intensity as long as the catch per unit of effort is above point C (the minimum CPUE needed to operate in site 2 located at 45 km).

Accordingly, for the more distant patch 3, fishing intensity occurs over time as long as CPUE is equal to or greater than the corresponding CPUEmin (point D). The biomass remaining in the long run in sites 1, 2, and 3 will result in $X_{D'} > X_{C'} > X_{B'}$. Therefore, patches located at different distance from port of origin, and with equivalent biomass in the absence of fishing mortality, will end up having final differential biomass levels determined by heterogeneous fishing intensity resulting from different minimum CPUE needed to pay for the steaming and fishing costs of harvesting in different locations over space.

For different fishing sites (s) located at the same distance from port with different initial biomass levels (X_s) (see Figure 10.5a), the X_s open access trajectory of



(a)

(b)

Figure 10.5 Site-specific biomass and CPUE over time located at the same distance from port.

the three sites will tend to converge to the same biomass level (i.e., homogenizing with exploitation biomass available in sites 1, 2, and 3 over time).

Therefore, under open access, the initial biomass differences among sites located at the same distance from port will tend to become zero over time as effort reaches its bioeconomic equilibrium. Analogously, initial heterogeneous $\mathrm{CPUE}_{s,t}$ (A in Figure 10.5b) will tend to become homogeneous for sites located at the same distance from port (B in Figure 10.5b). In Figure 10.6, we consistently observe that as quasi profits are greater than zero in specific sites, there is effort being allocated in proportion to the relative quasi profits obtained in different fishing sites.

Therefore, what drive the spatial fishing behavior are the quasi profits obtained over time in different fishing sites. If they are positive in a specific site,

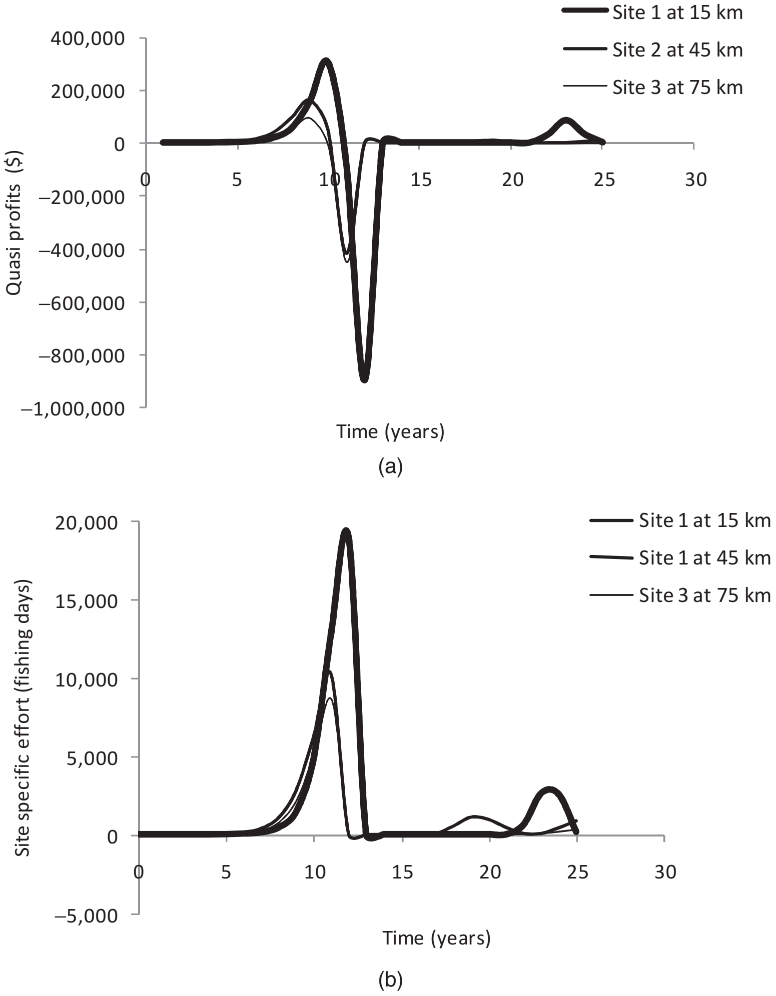


Figure 10.6 Site-specific fishing effort and quasi profits of variable costs over time.

fishermen will undertake fishing intensity; otherwise, they will not allocate their effort in that specific site in the next period of time.

10.4 Spatial management of fisheries

In the transition from single species to ecosystem consideration of fisheries management, spatial management of single stocks and metapopulations have been under consideration and experimentation in the last decade. These last sections of the chapter discuss first the effect of spatial management of fisheries using marine-protected areas (MPAs) with nearby and far-away alternative port locations. Then, it proceeds to show the effects of location of an MPA in a situation of a metapopulation with source–sink configuration.

10.4.1 An MPA to manage a single-stock population under open access

Spatially managing a single-stock population through the use of an MPA requires considering the effect of locating it with respect to the port of origin of the fleet targeting the resource. In Figure 10.7, we have the spatial fishing behavior when the MPA is located alternatively near port (Figure 10.7a) or far away from the port of origin (Figure 10.7b). As we can see in this figure, the model properly predicted no fishing in the alternative locations of the MPA. In both cases, because of steaming costs, effort tends to be allocated nearer to the port of origin of the fleet.

Under open access, we have the trajectories of species biomass with respect to time and effort in three possible situations: (1) without an MPA, (2) with an MPA located near port, and (3) with an MPA located away from port. We can see in Figure 10.8 that without MPA, species biomass falls faster than the scenarios where an MPA is established.

As expected, when the MPA is located near port, biomass tends to be at higher levels over time in the process of converging to bioeconomic equilibrium. The relative difference of bioeconomic equilibrium biomass for the three scenarios will depend on the steaming cost of the specific fishery.

The following section addresses the use of MPAs as spatial management strategy of marine fisheries, summarizes the cost and benefits of its use, and reviews the recent modeling efforts developed to understand their possible performance under variety of assumptions of resource and effort dynamics over space and time.

10.4.2 Spatial management of fisheries: MPAs

An MPA is a geographic area with discrete boundaries that has been designated to enhance the conservation of marine resources. Marine reserves are often cited as forming a new strategy for stock and ecosystem recovery. The potential benefits of establishing marine reserves include (1) protection of spawning biomass, (2) providing a recruitment source for the surrounding areas, (3) supplemental restoring of fished areas through emigration, (4) maintenance of natural population age structure, (5) maintenance of undisturbed habitat, and (6) insurance against management failures in fished areas.

MPAs benefit adjacent fisheries through two direct mechanisms: (1) net emigration of adults and juveniles from the protected to the unprotected areas and (2) export of eggs and larvae that will eventually settle in unprotected habitats available for fishing. The former will depend on the degree of resource mobility over space (e.g., Walters, 2000), and the latter on egg and/or larval dispersal processes. Gell and Roberts (2003) reported that within marine reserves, populations tend to increase in size and individuals live longer, and increase their reproductive contribution.

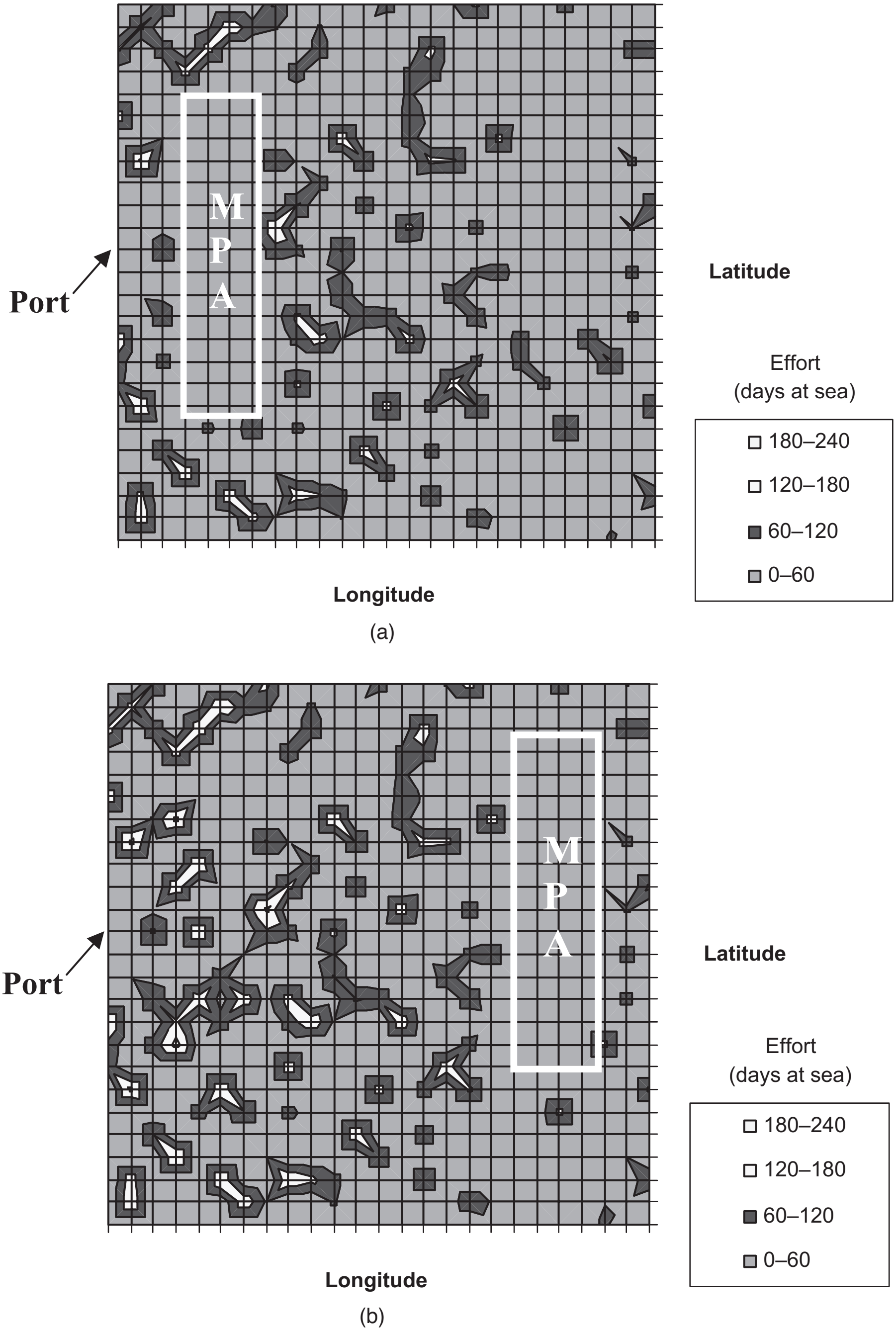


Figure 10.7 Spatial behavior of fishing intensity with alternative location of MPA with respect to port of origin.

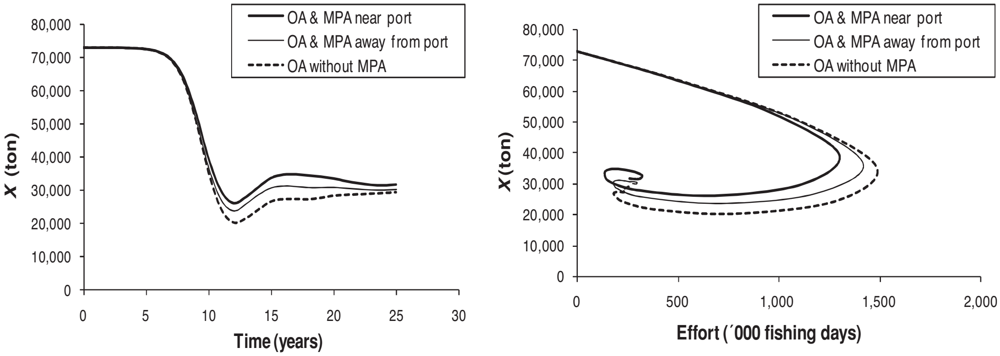


Figure 10.8 Effect of an MPA and its location under open access.

NRC (2001) provided a typology of MPAs that involve increasing levels of protection:

- *Marine Protected Areas*: A discrete area that has been designated to enhance the conservation of coastal resources and is managed by an integrated plan that includes MPA-wide restrictions on some activities as oil and gas extraction, and higher levels of protection on delimited zones, designated as fishery and ecological reserves within MPA.
- *Marine Reserve*: A zone in which some or all of the biological resources are protected from removal or disturbance. This includes reserves established to protect threatened species or endangered species.
- *Fishery Reserve:* A zone that precludes fishery activity on some or all species to protect critical habitats, rebuild stocks, provide insurance against overfishing, or enhance fishery yield.
- *Ecological Reserve*: A zone that protects all living marine resources through prohibitions of fishing and removal or disturbance of any living or nonliving marine resource, except as necessary for monitoring or research to evaluate the effectiveness.

According to Clark (2006), experience with existing marine reserves has demonstrated that fish communities can be reconstituted, sometimes quite rapidly, when fishing pressure is removed. This author also hypothesizes that marine reserves would actually help the fishermen by providing secure source of supply to otherwise depleted areas.

Before establishing an MPA, ecosystem managers should be aware of the potential costs and benefits involved.

As will be shown later in this chapter, an MPA will generate these desired effects only if it is located within the source area of the population. If located outside the main source area or in the sink one, the performance of the fishery will be likely to be worse than without the MPA. This is so because, for the same fishing effort level, fishing intensity (effort per unit area) will increase in the source area as a result of the reduction of the overall fishing area.

Therefore, to aid spatial management of fisheries, with source sink configuration modeling the potential bioeconomic effects of location and size of marine reserves seems fundamental.

10.5 A metapopulation with source–sink configuration

10.5.1 Management of metapopulations and source–sink theory

Dynamic pool models suppose that each individual has an equal probability of mating and spawning, and this has been referred to as *panmixia*. However, more recent studies of marine fish populations using trace elements, parasites, and genotypes have begun to discover genetic differentiation within demersal marine resources of continental shelves (e.g., Geffen *et al*., 2003), suggesting that metapopulations are fairly common, especially for sedentary or territorial species (Sinclair, 1987). Hence, the effective reproductive size of a population may be much smaller than its total population size, and reproductive age groups and spawning sites may not be equally successful in their reproductive activities throughout the species range (e.g., Smedbol *et al*., 2003).

Metapopulation theory has become an important focus for fisheries studies, but until recently few studies examined its practical implications for fisheries management. Metapopulations are composed of linked subpopulations distributed over space with interrelations.

Source–sink theory is now used to describe populations as local subunits linked by immigration/emigration, where incomplete mixing or extinction applies (e.g., Amezcua and Holyoak, 2000). Source–sink resources follow a specific metapopulation configuration where one or more local groups showing a positive rate of population growth, referred to as sources, also contribute to other local groups (sinks) on suboptimal habitats that do not contribute significantly to the next generation. The disruption of unrecognized source–sink configurations may lead to stock collapse. For metapopulations with a source–sink configuration, in addition to the size of the MPA, its location is mainly relevant with respect to source areas and the position of fishing ports used by fishermen targeting a resource. A common feature of coastal port-based fisheries not frequently considered in stock assessment modeling is the progressive expansion of the fleet to cover new grounds further from port.

Therefore, decisions regarding location, size, and linkages between MPAs and other components of ecosystems must be considered. Adopting an MPA as major management tool will require a shift in management emphasis from single-species management to spatial management of ecosystems. Oceanographic features, bathymetry, hydrography, and the transport of organisms into or out of MPAs can be critical factors in MPA design.

To aid decision making when spatially managing fisheries, the space–time bioeconomic approach provides a useful path to estimate possible effects of alternative spatial regulatory strategies.

10.5.2 Bioeconomic approaches to model the effects of MPAs

In recent years, theoretical and empirical studies have attempted to estimate the optimal size of marine reserves, e.g., Sumaila (1998), who determined the bioeconomically optimal size of a marine reserve for the Barents Sea cod fishery as a function of the transfer rate between the protected and the unprotected areas. Beattie *et al.* (2002) applied game theory within a spatial biomass dynamic model to evaluate the efficiency of MPAs in the North Sea, in both ecological and economic terms. Models have also been applied to site selection for MPAs for conservation of species with source–sink characteristics (Crowder *et al.*, 2000). Hannesson (1998) discussed the potential of marine reserves, and Anderson (2002a) extended Hannesson's analysis using sustainable catch and revenue curves to illustrate how marine reserves influence the proportion of stock available for harvest, and compared fishery performance with or without marine reserves.

A variety of approaches have been used to explore how biological and economic factors contribute to the evolution of exploitation patterns over space and time. Sanchirico and Wilen (2001) developed a simple biomass dynamic model for metapopulation exploitation, and Anderson (2002b) used a biomass dynamic approach for a two-patch stock and derived spatial bioeconomic equilibrium conditions for alternative migration assumptions.

Concerning location of MPAs, Smith and Wilen (2003, 2004) indicated the relevance of the proximity of source or sink areas to a fishing port, using an age-structured model.

The human element, including stakeholders' involvement in the planning and implementation stages of MPAs, is critical in determining whether an MPA will successfully meet its objectives or whether it will result in resentment and noncompliance by individuals and communities that face restrictions on current and future uses.

The main conclusions of the cited spatial modeling efforts provide insights into how marine reserves could perform, either as a primary fishery management tool or as one of a set of regulatory measures for sustaining fisheries over time. It generally concluded that:

- Reserve benefits are greatest for species that are sedentary as adults and have widely dispersing offspring.
- As mobility increases, reserve benefits diminish.
- At high rates of adult transfer between reserves and fishing grounds, reserves become ineffective.

10.6 A bioeconomic model for source–sink configurations

The following section adapts the model described above to include a source–sink configuration and explores the effect of alternative port locations A and B, which are nearby and distant from the source area, respectively.

10.6.1 Spawning and recruitment

For spawning and recruitment of a metapopulation with source–sink configuration, we have that $\sum_s \mathrm{SSB}_{s,t}$ from Equation 10.2 is the total *spawning* biomass from the *source area* over time. An important assumption of Equation 10.2 is that recruitment depends on the spawning biomass of the source area identified. This assumption is likely to be valid when the life cycle of species involves indirect development, i.e., when juveniles do not emerge directly from the egg to a local nursery area, but rather are a result of metamorphosis of planktonic larvae dispersing to recruit to geographic sites beyond those inhabited by the parental stock. Each site with specific geographic coordinates would contain several age classes, and each would have different densities.

Recruitment in the space–time bioeconomic model presented in the previous section was generated from adult biomass located in a subarea (e.g., ~10% of total area or 60 geographic cells) of metapopulation distribution. This aggregation was considered the source area. Effective spawning originated exclusively from adult biomass in this area. Recruits generated by a stock–recruit relationship using this source biomass only are distributed over the whole array the following year in both source and sink areas using the random (negative binomial) distribution. The residual biomass of mature source components becomes the input to a Beverton–Holt spawner–recruit model and used to generate next year's recruitment over the whole array. Especially for highly fecund invertebrates and species where suitable habitat for recruitment is limited, resulting in an effective plateau of recruit numbers, this seems a reasonable model to use. Other recruitment functions, like the ones discussed in Chapter 5, can also be applied to estimate the recruits to be distributed over space. In this case, the physical movement of individuals between unit areas was not modeled since spatial disaggregation is most relevant for low-mobility or sedentary resources.

10.6.2 Location of MPA for spatial management of a metapopulation

In a metapopulation with a source–sink configuration, the location of the MPA is a critical decision. If an MPA is located outside the source area, it is predicted to result in deteriorating biomass level and net revenues because fishing intensity (effort per unit area) will tend to increase in the unrestricted source area.

In Figure 10.9, we can see the effect of locating an MPA at source area in comparison to locating it in the sink area or just maintaining the fishery under open access without spatial management.

Results show that under open access, closing the source area results in final biomass (point A) greater than equilibrium biomass obtained by closing the sink area or not having a close area at all (point B). It should be pointed out that there is no improvement just by closing an area of stock distribution that is not a source of future recruitment.

Seijo and Caddy (2008) concluded that (1) inshore ports located close to an unprotected source area is a recipe for stock collapse, (2) closing at least

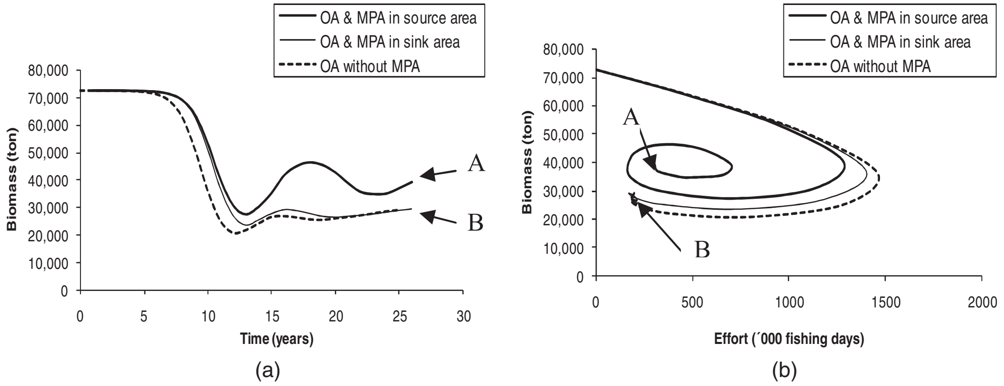


Figure 10.9 Effect of an MPA location to manage a metapopulation with source–sink configuration: (a) biomass over time; (b) biomass (E).

half the source area to fishing substantially mitigates the effect of port location and improves all performance variables regardless of port location, and (3) MPA established outside the source area might even accentuate the risk of stock collapse if, as a result, fishing intensity is diverted to the open access source area.

When a spatial closure is applied, the average distance harvesters travel from a port close to the source is predicted to increase for all levels of fishing intensity while distances traveled by fishermen from a port near the sink areas are predicted to decrease.

10.7 Migration in spatial models of fisheries

As species mobility increases, one could incorporate migratory components to represent changes in the spatial availability of the resource over time. There have been a number of contributions in the fisheries economics literature using Schafer–Gordon two- or three-patch models to illustrate migratory behavior of fish and the expected changes in fishing intensity over space (Anderson, 2002b; Armstrong and Skonhoft, 2006; Kar and Matsuda, 2008). These modeling efforts have usually assumed equilibrium conditions to arrive at analytical solutions.

Anderson (2002b) considered two stocks of the same species distributed in discrete "patches." Two types of biomass migration from patch i to patch j will be described: (1) density-dependent and (2) source–sink. The first migration type is calculated by:

$$M(X_{i,t}, X_{j,t}) = b\left(\frac{X_i}{K_i} - \frac{X_{j,t}}{K_j}\right) \tag{10.16}$$

In this case, fish migrate from higher density patches to lower density patches. The migration coefficient between patches is defined by b. When the expression is positive, there is migration into patch *j*. When the expression is negative, there is migration into patch *i*. Migration from patch *j* to patch *i* equals $-M(X_i, X_j)$.

For the second case, source–sink migration of biomass from patch *i* to patch *j* is represented by:

$$M(X_{i,t}) = \left(\frac{b}{K_i}\right) X_{i,t} \tag{10.17}$$

Migration from the source patch to the sink patch will be proportional to the size of the source stock. The ratio b/K_i is used to allow for comparisons to the density-dependent case. The loss of fish in area *i* is $-m(X_i)$. It should be pointed out that it is not practical to shift patches on the same fishing trip due to patches being distributed at different locations relative to a single fishing port and given the relative locations. The decision of which patch will be fished is discussed below. Long-run vessel profits in each patch are calculated as follows:

$$\Pi_1 = P\left(\frac{q}{K_1}\right) T_1\gamma_1 X_1 - (T_1C_1 + FC + \psi V_1) \tag{10.18}$$

$$\Pi_2 = P\left(\frac{q}{K_2}\right) T_2\gamma_2 X_2 - (T_2C_2 + FC + \psi V_2) \tag{10.19}$$

where T_i is number of trips per period taken when fishing in patch *i* and γ_i is portion of trip to patch *i* that is actually spent fishing (Equation 10.21).

$$\gamma_i = \frac{L_i - \frac{d_i}{s}}{L_i} = 1 - \frac{d_i}{sL_i} \tag{10.20}$$

y_i is the periodic harvest per vessel in patch *i* calculated by $y_i = \left[\frac{q}{K_i}\right] T_i\gamma_i X_i$, where *q* is the density-dependent catchability coefficient.

ψ is the vessel cost interaction coefficient. Anderson (2002) points out that a zero value for this parameter indicates that fleet size does not affect vessel costs. A positive value indicates congestion externalities and negative values indicate cooperation.

The equations for the interperiod change in stock size in both patches with density-dependent migration are:

$$X_{1,i+t} = X_{1,t} + G_1(X_{1,t}) - M(X_{1,t}, X_{2,t}) - V_1y_1 \tag{10.21}$$

$$X_{2,i+t} = X_{2,t} + G_2(X_{2,t}) - M(X_{1,t}, X_{2,t}) - V_2y_2 \tag{10.22}$$

Analogously, we obtain the source–sink migration equations replacing $M(X_{1,t}, X_{2,t})$ by $m(X_{i,t})$, and patch 1 would be the source patch.

Because vessels can switch patches over time, Anderson modifies the traditional Smith vessel change equation, obtaining an interperiod change in fleet size in each patch as follows:

$$V_{1,t+1} = V_{1,t} + \Phi_1\Pi_{1,t} + \Phi_s(\pi_{1,t} - \pi_{2,t}) \tag{10.23}$$

$$V_{2,t+1} = V_{2,t} + \Phi_2\Pi_{2,t} + \Phi_s(\pi_{1,t} - \pi_{2,t}) \tag{10.24}$$

where Φ_1 andΦ_2 are the entry–exit coefficients for patches 1 and 2 and Φ_s is the switching parameter. The second term captures the change determined by the entry or exit of vessels to the fishery that is assumed proportional to long-term profits. The third term will capture the switching of vessels between patches according to the relative short-term profits.

The system will reach joint bioeconomic equilibrium when long-run profits for both fleets are zero and when the catch in both areas equals the algebraic sum of growth plus migration (it occurs when Equations 10.18, 10.19, 10.21, and 10.22 equal zero simultaneously). Equilibrium stock size ($X_i{}^*$) in patch i is calculated in Equation 10.25 as follows:

$$X_i^* = \frac{K_i}{Pq_i}\left[\frac{C_i}{\gamma_i} + \frac{\mathrm{FC} + \psi V_i}{T_i \gamma_i}\right] \tag{10.25}$$

It is important to mention that there are some cases where it is not possible to solve for the equilibrium stock size autonomously when having a nonzero ψ (e.g., case with linearity assumptions).

10.8 Final remarks

Management questions that can be addressed with a tool like the one developed for this chapter include (1) what is the optimum closing period of a rotating harvest strategy for sedentary resources with different life cycles? and (2) what is the optimum size of an MPA?, among others.

Concerning management of metapopulations, we should also recognize that improvement of net benefits and potential reductions of undesired impacts may occur, however, for a source area close to a port, if enlightened community-based management leads to social self control and mutual surveillance of protected area by fishers.

In the next chapter, the complexities of environmentally driven fluctuating fisheries in a changing climate context are explored together with seasonality considerations in the bioeconomic analysis of fisheries.

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Chapter 11

Seasonality and long-term fluctuating stock

11.1 Introduction

This chapter presents simple ways of incorporating seasonality and long-term patterns in the bioeconomic analysis of fisheries.

In the first part of this chapter, we will address the problem of seasonal distribution of effort under open access using an age-structured bioeconomic model with seasonal spawning, hatching, and recruitment processes built in.

In the second part, we will model the long-term dynamics of stock fluctuations using a periodically varying carrying capacity. We will also present an age-structured bioeconomic model for environmentally driven fisheries (e.g., sardine and anchovy fisheries) that respond to long-term oceanic patterns of productivity and environmental conditions. This is done by using an environmentally driven recruitment function.

Seasonality in recruitment and effort dynamics is represented using the distributed delay model included in short- and long-run age-structured model applied to fisheries of short-lived species (e.g., shrimp and octopus fisheries).

Seasonality in bioeconomic modeling of fisheries has been reported using a Schaefer–Gordon approach for (1) estimating the effects of seasonal fluctuations of an open access fishery using periodic coefficients (Ardito *et al.*, 1993) and (2) determining whether rents are maximized or dissipated in an open access fishery within seasonal fishing (Kennedy and Hannesson, 2006).

Age-structured biological approaches have concentrated on individual growth seasonality inserting periodic functions in the von Bertalanffy growth function for demersal crustacean (Xiao and McShane, 2000). Even though there are rare intra-annual bioeconomic modeling efforts using an age-structured approach to account for recruitment seasonality (Seijo *et al.*, 1998), Bowden (2005) indicated that most species exhibited pronounced recruitment seasonality. Teh *et al.* (2007) studied seasonality patterns of reef fisheries in Malaysia and

Van Zwieten *et al.* (2002) studied the effects of inter-annual variability, seasonality, and persistence of the industrial pelagic purse-seine fishery of northern Lake Tanganyika. More recently, Kanaiwa *et al.* (2008) evaluated the performance of a seasonal, sex-specific, and size-structured stock assessment model with respect to the temporal pattern of recruitment. Accounting for this fundamental biological process of seasonal occurrence becomes critical for short-lived species exposed to exploitation rates during a year in which the adult stock will have only one or two opportunities to contribute to new recruits to the population. Therefore, designing age-structured bioeconomic models with recruitment seasonality is required to properly estimate the possible biological and economic impacts of the temporal specification of closed seasons among other fishery management strategies.

11.2 Modeling recruitment seasonality

In previous chapters we have dealt with inter-annual bioeconomic modeling and analysis and used parameter sets for fisheries of species of more than 3–4 years of longevity.

For short-lived species (1–3 years of life cycle), it is critical to understand and be able to represent intra-annual and seasonal biologic processes, like spawning and recruitment, and economic processes, like seasonal allocation of effort along the year.

Seasonal modeling of recruitment using an age-structured dynamic bioeconomic model allows estimating the spawning stock that remains in the water when the reproduction process occurs. Therefore, the number of recruits can be estimated and distributed seasonally in accordance to species-specific spawning and hatching periods that take place with different time duration. Accordingly, for management purposes, it is necessary to properly determine the effect of duration of fishing seasons and their occurrence during the year. Allowing for as many spawners as possible to remain unharvested will foster (*ceteris paribus*) a more robust recruitment.

We would usually have a good notion of peak periods for spawning, hatching, and recruitment with some knowledge of the length of such periods. What is clear, however, is that not all the mature female stock spawn in a specific week or month of the year, but that there is a distribution of spawning within a specific period. The same occurs with hatching of eggs and the corresponding recruitment to age 1 (weeks or months) of the population. Understanding and representing the above-mentioned dynamic processes of a fishery aids management decisions concerning properly setting closed seasons to protect critical spawning, hatching, and recruitment processes.

To represent these biological processes that occur intra-annually in a fishery, we will use the distributed delay model developed by Manetsch (1976), and applied to model recruitment seasonality and effort allocation during a fishing season by Díaz de León and Seijo (1992) and Seijo *et al.* (1998). The model is based on the Erlang probability density function (see Appendix 2 for details).

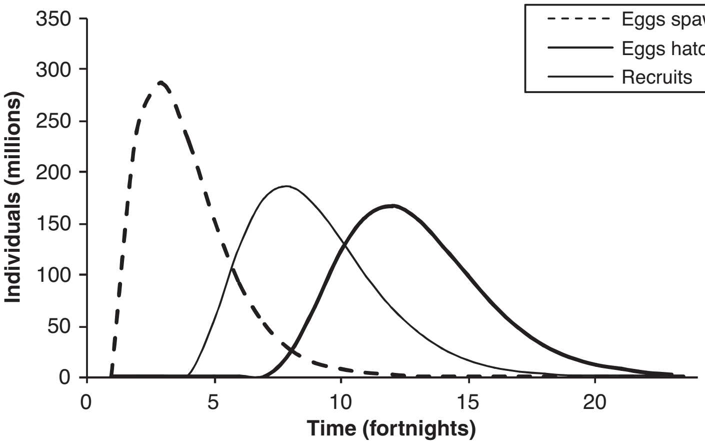


Figure 11.1 Seasonal spawning, hatching, and recruitment processes in fisheries.

Spawning, hatching, and recruiting of individuals to the population structure are shown in Figure 11.1, where we can see that the processes occur sequentially in time during a year. The spawning of eggs depends on the number of adult females and the corresponding average fecundity. In this illustration, it occurs, as shown within the first 5 months of the year, with a peak at 45 days after the spawning process started. Later on, for instance, in 60 days of incubation period, the hatching process begins and eventually results in post-larvae recruiting to the population between 3.5 and 12 months, with a peak in sixth month of the year.

As information becomes available from the fishery, one could include specific natural mortalities for the spawning and hatching processes. Currently, the Excel model considers an overall constant natural mortality. As discussed in Chapter 5, age-specific natural mortalities can also be included in this type of models.

The implication of being able to model the three processes with their corresponding seasonal distribution over time allows the possibility of estimating the potential effect of alternative timing of fishing season, and possibly, area closures during the spawning process. For different species, there will be different timing of spawning, hatching, and recruiting periods so that the bioeconomist should obtain from biologists the best scientific data concerning lengths of periods and their corresponding peaks for each of the above-mentioned processes. Therefore, the estimation of future recruits will require calculation of the number of adult female entering the spawning process and the average fecundity of the species. Because we are dealing with short-lived species, age-specific fecundity becomes irrelevant due to the fact that most of the short-lived species spawn once or twice during their life cycle.

In Figure 11.2, we can see the distribution of recruitment over a period of 3 years. Notice that the first recruitment is the one presented in Figure 11.1. In this figure, we have not included the underlying spawning and hatching processes.

A short- and long-run dynamics model for the fishery was developed considering seasonality of recruitment and effort of heterogeneous fleets. In addition

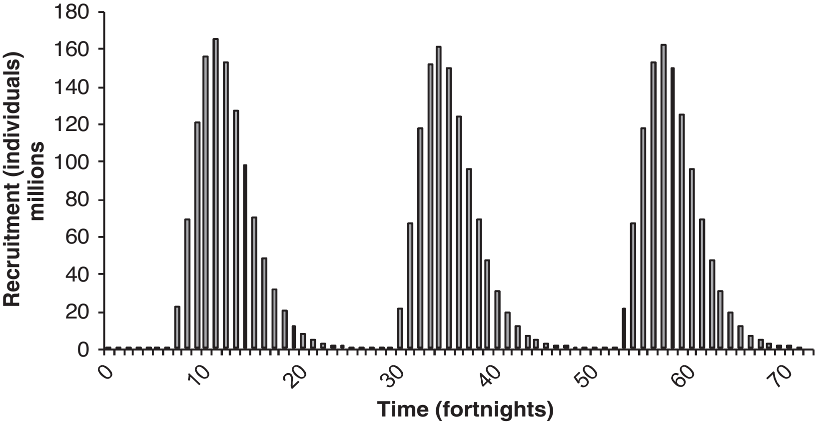


Figure 11.2 Seasonal recruitment of individuals to the population over time.

to Equations 11.2–11.6, a summary of the equations used in this model, and the corresponding parameter set (Tables A3.2 and A3.3) are included in Appendices 2 and 3 at the end of this text.

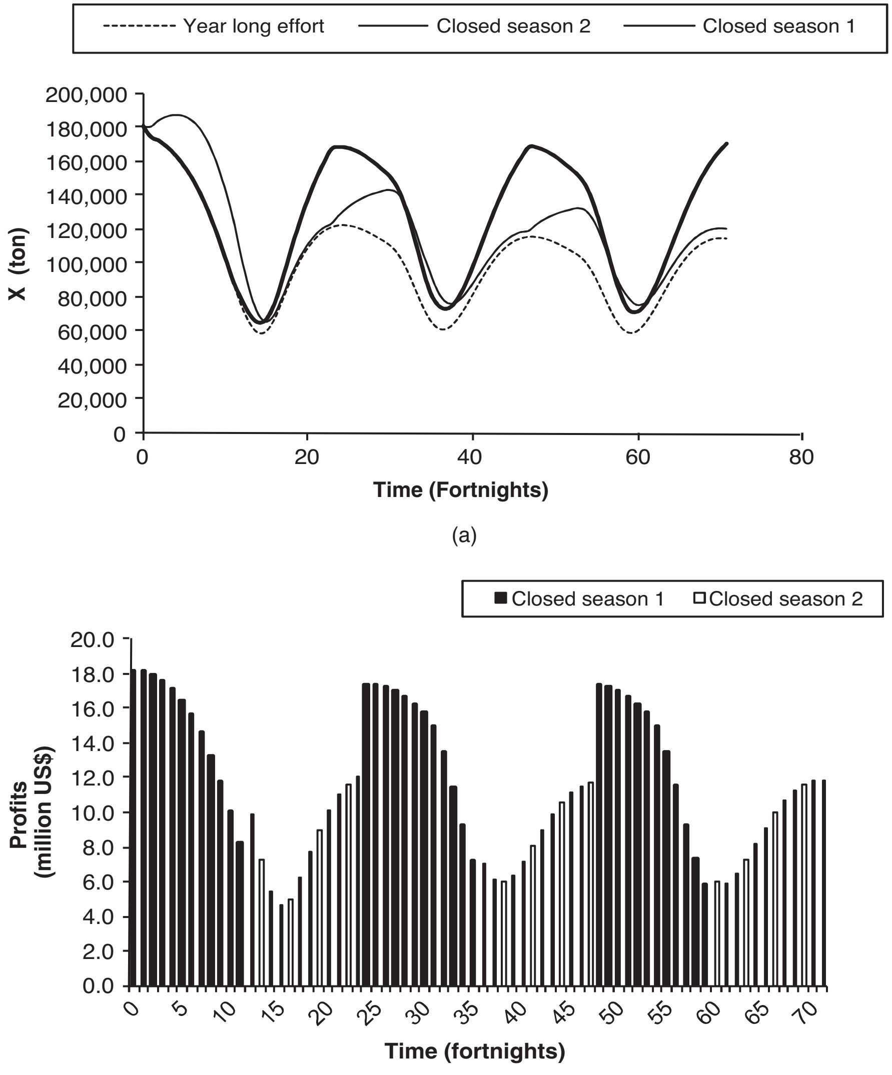
In Figure 11.3, we can observe the seasonal distribution of biomass under three intra-annual allocation strategies of effort: (1) year-long effort, total annual effort allocated along the year, (2) closed season 1, effort allocated during the first 6 months of the year, and (3) closed season 2, effort allocated during the last 6 months of the year. We can observe that there is a considerable difference in biomass when selecting different months of the year for the closed season. Closed season 1 is the one that generates the highest improvement in the intra-annual effort management.

In Figure 11.3b, we can see that profits are again higher when having closed season 1 that considers the sequential spawning, hatching, and recruitment processes occurring as represented in Figure 11.1. Therefore, it is fundamental for the bioeconomist to have a good understanding of the underlying biological processes leading to observed recruitment in a fishery.

11.3 Optimum allocation of seasonal effort

In order to optimally allocate effort in a seasonal fishery, the following approach is followed.

With the seasonal model described above, we estimate dynamically the number of eggs spawned [$S_t(\mathrm{SSB}_t)$], the hatching rate (H_t), and the resulting seasonal recruitment (R_t), as shown in Figure 11.4. Also, endogenously determine, as shown in Chapter 5, the dynamics of the population structure (N_{it}), age-specific biomass (X_{it}), and spawning biomass (SSB_t). In addition to these biological variables, seasonal catch, costs, revenues, and profits are also estimated. As a result, biologic and economic fishery performance variables become an input to the fishery management process that regulate, for instance, effort and fishing season (input controls), and could also establish output controls such as TACs. These



(a)

(b)

Figure 11.3 Biomass and profits of seasonally managed a fishery of short-lived species.

regulations become constraints to the optimization procedure devised to estimate the optimum effort allocation within the season to maximize profits over time. In this model, this can be done by using the solver function available in Excel software.

11.4 Long-term patterns in small pelagic fisheries

In the previous section, we developed an approach to deal with short-term patterns of recruitment and effort within a year. In this section, we present simple

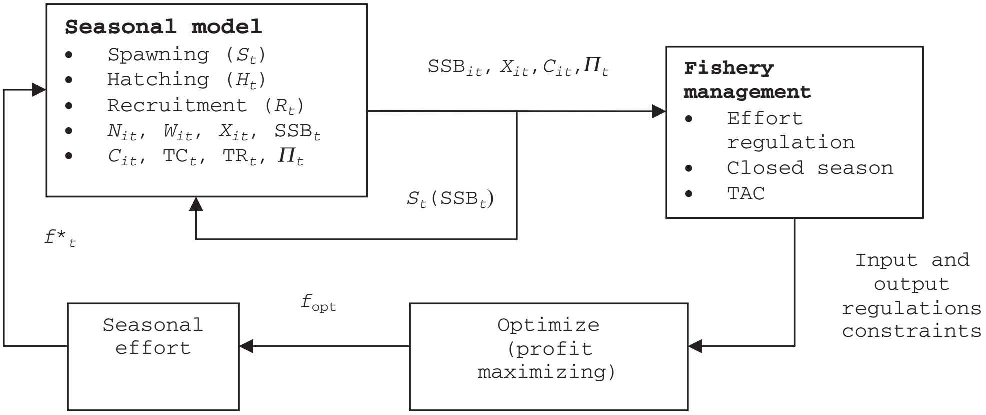


Figure 11.4 Conceptual model for optimizing intra-annual effort in a seasonal fishery.

approaches for including periodic fluctuations in recruitment long-term patterns. We will do that first by relaxing the assumption of constant carrying capacity of the Schaefer–Gordon model, and secondly, by making dynamic recruitment a function not only of spawning stock but also of critical environmental factors, such as water temperature or nutrient availability, in the age-structured bioeconomic model. In both approaches, we will use a sine function to represent the long-term fluctuating pattern in stock abundance.

Large fluctuations of fish stocks and long-term changes in human harvest of marine resources are well known from long before modern exploitation started and harvesting technology became efficient enough to make significant stock reductions (Hjort, 1914; Jakobsson *et al.*, 1995). Historical long-term changes in stock abundance have been related to climatic changes, as pointed out by Øiestad (1994). Fish stocks seem to fluctuate over time in relation to warm and cold periods in ocean waters.

More recently, Kliashtorin (2001) found that “populations of the most commercially important Atlantic and Pacific fish species—Atlantic and Pacific herring, Atlantic cod, European, South African, Peruvian, Japanese and Californian sardine, South African and Peruvian anchovy, Pacific salmon, Alaska pollock, Chilean jack mackerel, and some others—undergo long-term simultaneous oscillations. Total catch of these species accounts for about 50% of total fish harvest over Atlantic and Pacific.” The study also found that even though the anomaly of global air–surface temperature is correlated with the long-term dynamics of marine fish production, it is of poor predictive significance because of high inter-annual variability. The author suggested the use of the Atmospheric Circulation Index (ACI) for having higher correlations ($r = 0.70$–0.90), with long-term fluctuations of the main commercial fish stocks and lower inter-annual variability.

Based on these findings, bioeconomic modeling of pelagic fisheries should account for fluctuating periodicities of fish stocks of about 55 years, as estimated through spectral analysis of time series of ACI and of catch statistics (Kliashtorin, 2001).

11.4.1 Time-varying carrying capacity of the Schaefer–Gordon model

The aggregate Schaefer–Gordon model discussed in Chapter 2 can be easily modified to incorporate long-term fluctuating patterns in the carrying capacity of the ecosystem sustaining the target species. To do that, we relax the constant carrying capacity assumption and make it a function of time using a sine function representing the long-term natural fluctuation in stock biomass. For each fishery, specific observations should determine the periodicity of the cycle and the corresponding amplitude. As a result, our biomass growth function is now expressed as:

$$\frac{dX}{dt} = r X_t \left(1 - \frac{X_t}{\overline{K} - \sigma_K \sin\left(2\pi \frac{t}{\text{cycle}}\right)} \right) - q E_t X_t \tag{11.1}$$

where $\overline{K}$ is the average carrying capacity, σ_K is the amplitude of the carrying capacity, and "cycle" is the fluctuation period.

11.4.2 Dynamics of an environmentally driven fishery

To illustrate the global pattern model with fluctuations in stock biomass, we use the equations previously presented in Chapter 2 with Equation 11.1, solved numerically using Euler numerical integration with DT = 1, as follows:

$$X_{t+1} = X_t + r X_t \left(1 - \frac{X_t}{\overline{K} - \sigma_K \sin\left(2\pi \frac{t}{\text{cycle}}\right)} \right) - q E_t X_t \tag{11.2}$$

The parameter set used for this model is included in Table 11.1. For this illustration, carrying capacity is expected to fluctuate with respect to the average K (3.5 million tons) upward and downward up to 1.5 million tons using the sine function included in Equation 11.2. All other parameters are used for equations of the Schafer–Gordon model, as defined in previous chapters.

In a fishery with fluctuating carrying capacity, we would have to determine biomass and catch target and limit reference points (TRP and LRP, respectively)

Table 11.1 Parameter set used in modeling the fluctuating long-term pattern of the fishery

Parameters	Symbol	Value	Units
Carrying capacity	K	3,500,000	ton
Intrinsic growth rate	r	0.36	1/year
Unit cost of effort	c	45,000	US$/vessel/year
Price of species	p	150	US$/ton
Catchability coefficient	q	0.0004	1/vessel
Exit/entry parameter	ϕ	0.002	vessels/US$
Amplitude of K fluctuation	σ_K	1,500,000	ton
Environmental cycle	cycle	55	years

over time because there is no equilibrium biomass or sustainable yield. In the case of biomass, we can specify target biomass over time ($X_{t,\mathrm{TRP}}$) proportional to the time-varying carrying capacity as follows:

$$X_{t,\mathrm{TRP}} = \lambda K_t \tag{11.3}$$

where λ is a parameter value that would reflect biomass either at 0.5 (half the maximum biomass at that point in time) or any other value higher than that, which would tend to approximate biomass at maximum profits.

On the other hand, we can specify a biomass limit reference point over time for each year of the carrying capacity fluctuating period as follows:

$$X_{t,\mathrm{LRP}} = \tau K_t \tag{11.4}$$

where τ is the proportion of biomass below which the reversibility of stock collapse would be compromised. As mentioned in Chapter 6, a limit reference point is a level for variable that we would not like to reach or exceed. For species biomass, specification of this value would depend on species' longevity and vulnerability. Values for parameter τ are usually found in the interval of [0.2, 0.4].

In Figure 11.5, we have dynamic biomass trajectories of a fluctuating stock fishery under open access at target reference and limit reference points. Biomass target reference points are specified with $\tau = 0.3$ and $\lambda = 0.65$.

We can observe that open access biomass for this species tends to be close to or below the biomass dynamic limit reference points for the bioeconomic parameter set provided in Table 11.1.

Management of fluctuating stock fishery, like the one just described, can use either input or output controls, as those discussed in Chapter 7, which would have to be updated on a yearly basis to provide proper follow-up to stock fluctuations resulting from environmental factors.

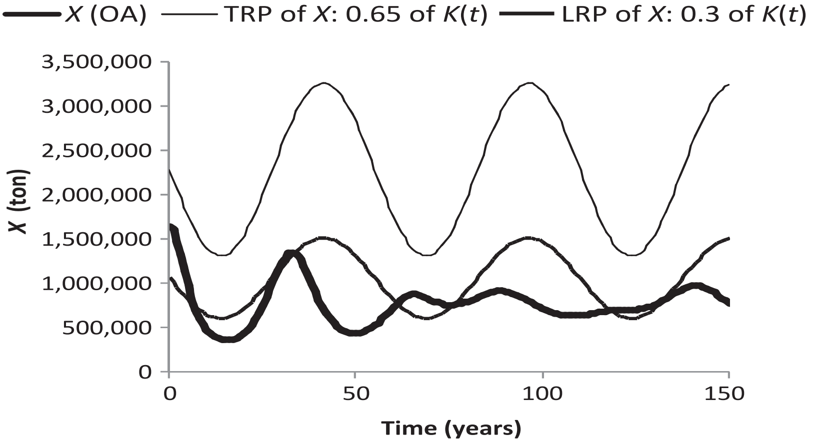


Figure 11.5 Fluctuating biomass at dynamic X_{TRP}, X_{LIM}, and unregulated open access X_{OA}.

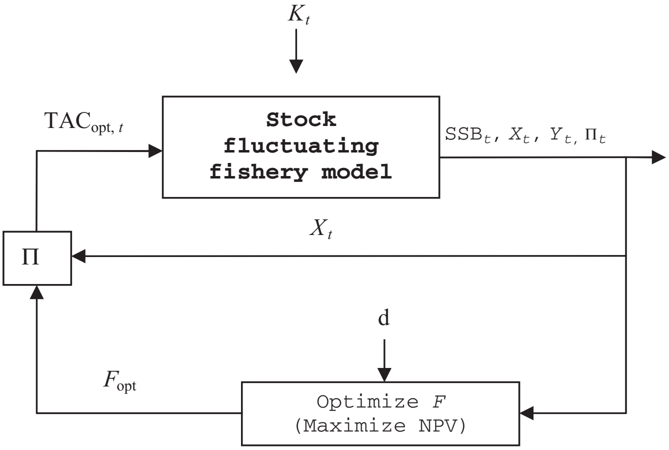


Figure 11.6 Optimum dynamic TAC in a stock fluctuating fishery.

In the absence of equilibrium conditions that would allow for analytical solutions, a simple approach for determining a heuristic optimum control of the fishery is presented in Figure 11.6.

In this figure, we have the dynamic model for the fluctuating fishery receiving the input of a dynamic time-varying carrying capacity (see denominator of Equation 11.2), determining a pattern of periodic stock fluctuations. For alternative rates of discount reflecting different prices of time, fishing mortality is optimized to yield maximum net present values. This F_{opt} is then multiplied by time-varying stock biomass to determine the corresponding optimum TAC over time.

In Figure 11.7, we can observe the trajectories of biomass, catch, and profits over time under unregulated open access and under a dynamic TAC_{opt}. Because of exogenous fluctuation of carrying capacity, there are no possibilities for reaching bioeconomic equilibrium in the fishery. Therefore, catch and profits will fluctuate in response to oscillations of resource abundance through time.

The dynamics of biomass under open access is, as expected, below biomass levels, which can be achieved as a function of dynamic TAC (Figure 11.7a). We can also observe that profits are always positive when the TAC is in place under the assumption that there is perfect enforcement and compliance (Figure 11.7c).

For this illustration we use a cycle of 55 years, as the findings of Kliashtorin suggested. As knowledge progresses and long-term fisheries-specific evidence is available, the bioeconomist should update the parameter set concerning environmentally driven changes in carrying capacity over time.

11.5 Long-term pattern of fluctuating environmentally driven recruitment

It is typical of most fish that they spawn vast numbers of eggs, of which only a minute proportion survive to become recruits. In early stages of the life history,

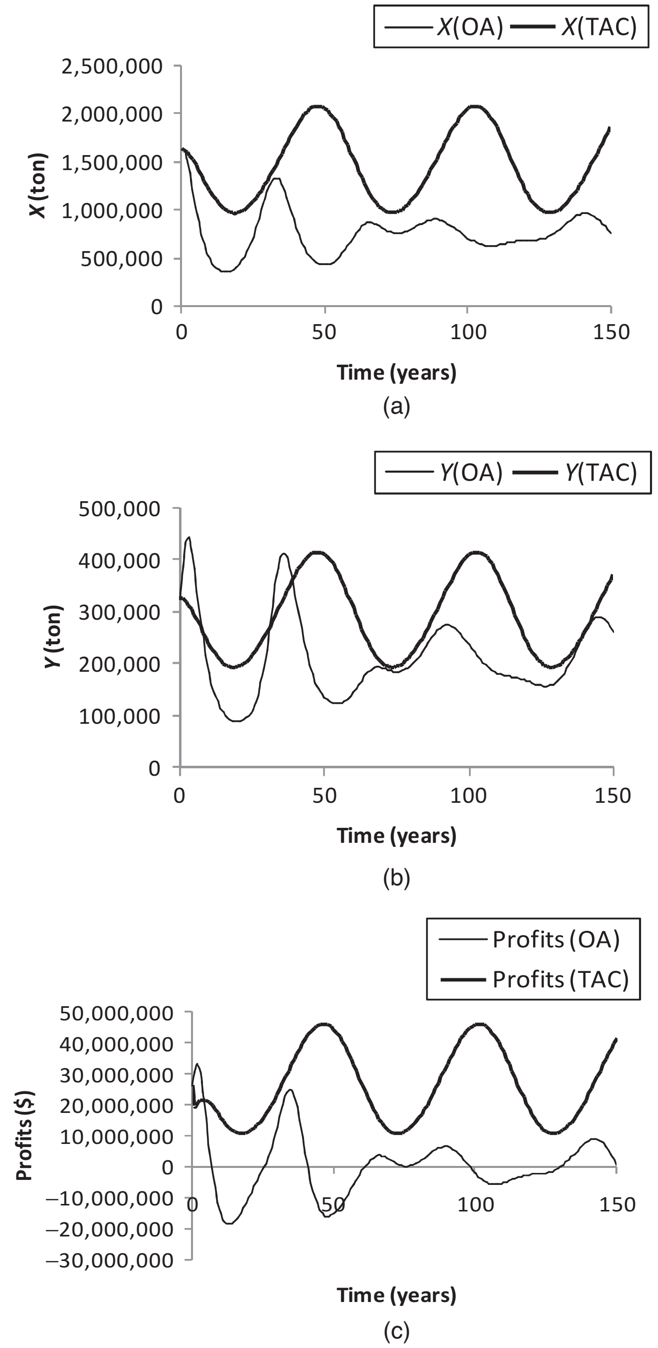


Figure 11.7 Biomass, catch, and profits of a fluctuating fishery under open access as a function of dynamic TAC.

young fish are very small and vulnerable to adverse conditions, particularly to predators and shortage of the right kind of food. As a consequence, the number of annual recruits typically fluctuates very greatly which has a corresponding effect on the size of the fished stock and the success of the fishery.

Even more profound are the consequences of systematic trends, upward or downward, in recruitment due to climatic events, and the prolonged failure of recruitment due to excessive depletion of the parent stock. A combination of such circumstances has led to the collapse of some of the world's greatest fisheries during the last 50 years, not all of which have recovered even though fishing ceased. From the turn of the century, when the great Norwegian fisheries scientist Johann Hjort first suggested that shortage of food at a critical stage in the early life history was the key factor determining recruitment, the search for an understanding of the long-term patterns of recruitment processes has continued.

Although some valuable clues are emerging, it has to be admitted that the mechanisms are still largely obscure. The reasons for these are not far to seek. It is extremely difficult to measure accurately at sea, on the necessary scales of time and space, what is happening in the early life of fish. Success or failure of recruitment, which may not be manifested unless the fish are several years old, can be due to a variety of causes. Although biological factors such as food, predators, and diseases are always important, their effect is mediated through the physical and chemical conditions in the sea at the time. Currents, turbulence, stratification, and wind stress are all significant. Thus, upwelling regions, although potentially highly productive, are also unstable and liable to generate extreme variation and systematic trends in recruitment, as instanced by the disappearance of the California sardine and the periodic collapse of the Peruvian anchovy due to the El Niño phenomenon.

The prize, in terms of the gain of useful knowledge, from a better understanding of the processes of recruitment, is therefore great, but the scientific challenge is formidable, in both concept and logistics. The problems go to the heart not only of physical and biological oceanographic science but of many ancillary disciplines such as fish physiology, nutrition, and behavior. It might be thought that, in such circumstances, a high degree of international cooperation would have developed to tackle problems which are of universal significance in the utilization of living marine resources.

Then, the main question of this section is: how can fisheries bioeconomics deal with this uncertain biological process of recruitment when modeling fisheries containing species highly sensitive to changes in environmental conditions (e.g., small pelagics like the ones mentioned above)?

A simple way of doing it, using an age-structured bioeconomic model that considers explicitly dynamic recruitment, is by introducing in the equation estimating the number of recruits over time, an environmental parameter that seems to be more correlated to the fluctuations in fish harvesting over long periods of time. This is presented as follows:

$$R_t = \mathrm{SSB}_t \, e^{(\varphi_1 - \varphi_2 \mathrm{SSB}_t + \varphi_3 \mathrm{STA}_t)} \tag{11.5}$$

where φ_1 is the density-independent parameter, φ_2 is the density-dependant parameter, and φ_3 is the environmental parameter. STA_t is the long-term periodic surface water temperature anomaly represented by a sine function as follows:

$$\mathrm{STA}_t = -\sigma_{\mathrm{temp}} \sin\left(2\pi \frac{t}{\mathrm{cycle}}\right) \tag{11.6}$$

where σ_{temp} is the amplitude of the sine function and cycle represents the fluctuation period.

Equation 11.5 presents an environmentally driven Ricker recruitment function that considers density-dependent and independent parameters as well as critical environmental variables like the ones discussed above. In this simple case, the environmental factor considered is surface water temperature. Other critical environmental indices such as the ACI, mentioned above, could be included in an environmentally driven recruitment function.

Figure 11.8 clearly shows the dynamics of fluctuating fisheries like small pelagics (i.e., sardines of California, Japan, Peru, and Chile, and anchovies in Peru). The dynamics observed in this figure express the long-term patterns described by Kliashtorin (2001) whereby biomass fluctuates with certain periodicity, causing periods of relatively low abundance and fishery collapse, as shown by the catch trajectory of Figures 11.8c and 11.8d.

Later on, because of favorable environmental conditions of global scale, biomass rose again, stimulating vessels to enter the fishery and experience increasing catch per unit of effort, even as effort increases over time until biomass peak is reached and a new downward trajectory begins with unfavorable environmental conditions.

We can also observe the profits trajectory which becomes negative during the period of low levels of abundance, causing most or all vessels to exit the fishery for long periods until biomass enters a new recovery period with favorable environmental conditions.

We can also explore biomass fluctuations with and without exploitation rates. By doing so, we observe:

1. The level at which biomass falls with different exploitation rates.
2. The amplitude of low biomass periods which are substantially greater with exploitation.
3. The higher the exploitation rate, the longer the recovery period will be.

The reader can explore in the Excel model “Fluctuating fisheries” possible environmental conditions concerning long-term oceanic patterns.

A key operational question for stock fluctuating fisheries like the ones modeled in this chapter is: What should the vessel capacity be to deal with possible states of nature determining the length of periodic cycles in carrying capacity of the ecosystem that sustains the fishery?

In Chapter 12, we acknowledge that climate change and other sources of oceanic variability may result in different length of long-term cycles of stock abundance, and therefore present a simple approach to deal with them, including

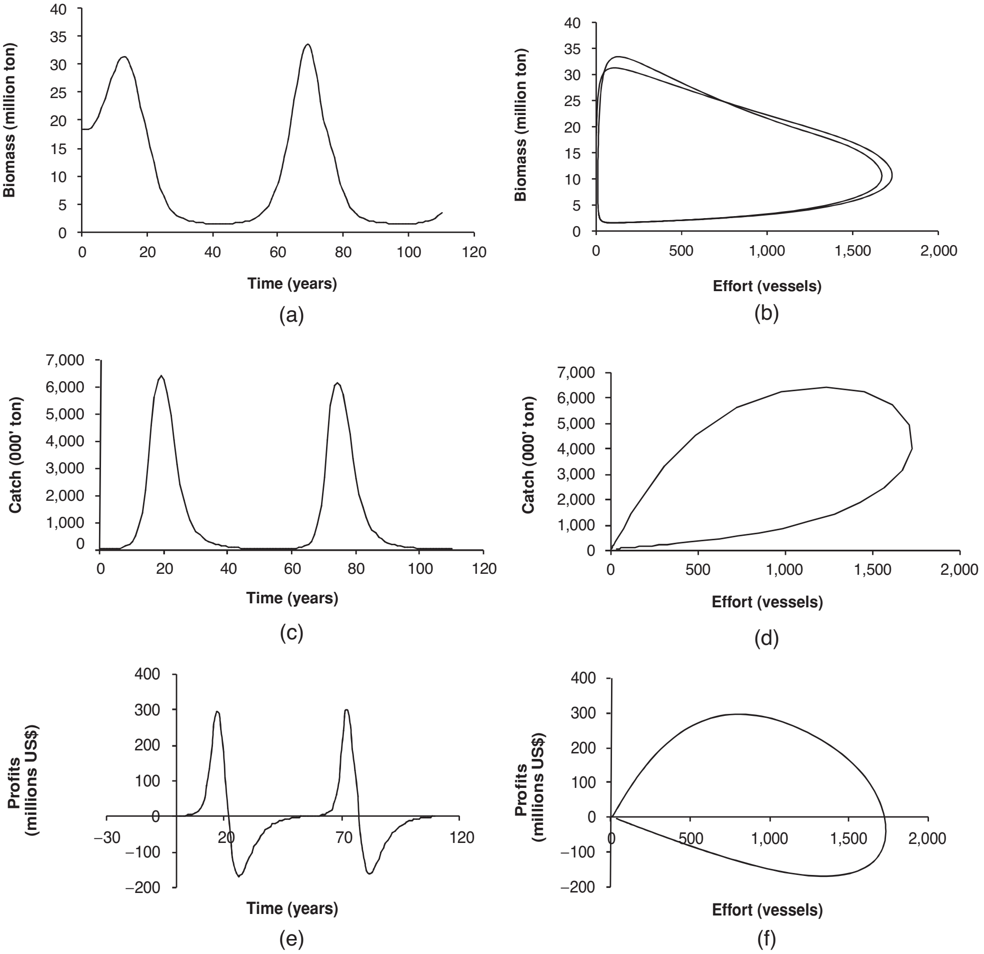


Figure 11.8 Dynamics of biomass, catch, and profits in an environmentally driven fluctuating fishery.

decision theory to aid in answering the question of the adequate vessel capacity to avoid exceeding LRP for spawning stock biomass.

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Chapter 12

Dealing with risk and uncertainty

Fisheries management, in the last few decades, has learned that population dynamics is affected by factors about which information is usually incomplete. Bioecological factors that play a role in population dynamics and bioeconomic analysis are often unknown or their relevance is unclear. As shown in Chapter 9, fishing a specific target species may be affected by ecological as well as technological interdependencies occurring between species and fleets. Spatial complexities, like the ones presented in Chapter 10, involve not only understanding and estimating resource and fisher behavior over space and time but also studying the dynamics of oceanographic processes dispersing larvae that will eventually settle in source or sink areas where habitat and food availability are critical for defining the dynamics of metapopulations. The extent to which population dynamics are affected by the surrounding ecosystem is often very complex and should be accounted for. How environmental fluctuations, as discussed in Chapter 11, affect fish populations on a local or global scale is largely unknown. Besides the observed periodicities of such fluctuations and the correlations with fish harvesting recently identified, the underlying cause–effect mechanisms are yet to be identified with reasonable certainty.

But not only should fisheries management acknowledge that fish population dynamics are complex and influenced by factors that are usually poorly understood, it should also recognize that fishers' behavior over space and time is difficult to predict and more so to effectively avoid or mitigate overexploitation and overcapacity. Managing fisheries by prescribing fishing effort requires detailed knowledge regarding factors that influence fishing behavior, which in turn can vary, depending on fishermen's cultural background and context, fishing technology used, and perceptions and strategic behavior affecting compliance to the regulatory scheme in place.

In order to manage fisheries successfully, in addition to having in place adequate institutional structures that clearly allocate property rights to resource users (individual or community rights), and wisely selecting regulatory input and/or output controls (like the ones described in Chapter 7), it is a prerequisite to have information about the population dynamics of the species, the interaction of fish population with their environment and other species of the ecosystem, and the dynamics of fishers' behavior. As mentioned above, this is a complex task affected by complexities and stochasticities that demand responsible management that acknowledge the uncertainties and use decision-making approaches that consider them explicitly and systematically.

Hilborn and Peterman (1996), among others (Fogarty *et al.*, 1992; Berkson *et al.*, 2002), have identified a set of sources of uncertainty associated with stock assessment and management procedures, including uncertainty in (1) resource abundance, (2) model structure, (3) model parameters, (4) behavior of resource users, (5) future environmental conditions, and (6) future economic, political, and social conditions. To deal with these variety of uncertainties, it was suggested, in the Lysekil meeting (FAO, 1995), to use Bayesian and non-Bayesian decision theory and the incorporation of limit and target reference points to manage fisheries. More recently, growing evidence of climate change effects on fisheries is also adding complexities to the set of sources of uncertainty mentioned above.

Evidence reported by Cochrane *et al.* (2009) indicate that climate change is modifying the distribution of marine and freshwater species. Species are being displaced toward the poles and are experimenting changes in the size and productivity of their habitats. It is also expected that ecosystem productivity will tend to decrease in tropical and subtropical ocean areas and to increase in higher latitudes.

Higher temperatures in marine and freshwater ecosystems are likely to affect physiological processes of species causing positive as well as negative effects in fisheries. This will depend on species' sensitivity to changes in temperature and salinity as well as their mobility capacity to migrate to more suitable environments.

The above-mentioned study also reports that climate change is affecting the seasonality of critical biological processes. It is also modifying food webs with unpredictable consequences in fisheries production.

Possible impacts of climate change in marine fisheries include (1) changes in species abundance with effects in reproduction, recruitment, and individual growth patterns, (2) changes in ecosystem productivity that sustains fisheries, (3) changes in species availability and their spatial distribution patterns, and (4) changes in the spatial distribution of fishing intensity.

12.1 Climate change increases uncertainty in marine fisheries

Climate change increases uncertainty in fish production, imposing new challenges to risk assessment usually based on the probability of occurrence of past events. The scarce historical data of possible effects of climate change on fisheries may not be adequate to guide future expectations. The additional uncertainties (to those reported by Hilborn and Peterman, 1996) that fisheries managers and other decision makers are currently facing include possible responses and adaptations of fishers to gradual climate changes, and synergistic interactions between climate change and other stressors affecting coastal fishing communities (e.g., eutrophication, overfishing, runoff pollution from inadequate agriculture and livestock production practices, and the ability and resilience of fishing communities to overcome these multiple stressors of coastal areas).

This chapter presents simple ways of incorporating these growing uncertainties and associated risks in the bioeconomic analysis of fisheries. The uncertainty present in critical biological and economic parameters of most fisheries is illustrated through an application of decision theory to a stock fluctuating fishery, with and without mathematical probabilities, to answer specific management questions.

The risks of exceeding limit reference points of biologic and economic performance variables are illustrated through the use of Monte Carlo analysis (as mentioned in Chapter 6) applied to a situation of multiple fleets affecting different components of the population structure. A multifleet age-structured model, like the one developed in Chapter 9, is used for the estimation of the dynamic bioeconomic effects of alternative stock recovery strategies to meet LRP criteria. A simple bioeconomic approach for dealing with uncertainty and risk analysis is presented in Figure 12.1, linking the fishery bioeconomic model, management options and decision criteria with and without mathematical probabilities, and the corresponding risk analysis that estimates the probabilities of exceeding limit reference points through the use of Monte Carlo approach.

As pointed out in Chapter 8, this approach for the development of responsible management strategies for fisheries, accounting for inherent uncertainty in fishery systems and climate-change–induced risks, involve the following steps:

1. Identify the set of management questions relevant to the fishery and the ecosystem.
2. Undertake biological, economic, and social assessment of the fishery, i.e., estimate size and dynamics of the population structure, age structure of the harvest, costs and revenues of alternative fishing methods.
3. Select the performance variables and corresponding bioeconomic indicators for the fishery.
4. Establish limit and target reference points for the selected indicators.
5. Identify different states of nature for those fishery variables and parameters (i.e., recruitment seasonality, natural mortality, unit costs of effort, catchability coefficient) that involve high levels of uncertainty.
6. Determine if mathematical probabilities can be assigned for the occurrence of the identified states of nature under climate change.
7. Build decision tables with and/or without mathematical probabilities, depending on whether observations are available and likely to properly guide future climate expectations.
8. Apply different decision criteria, reflecting different degrees of caution or risk aversion, to select the fishery/ecosystem management strategy.

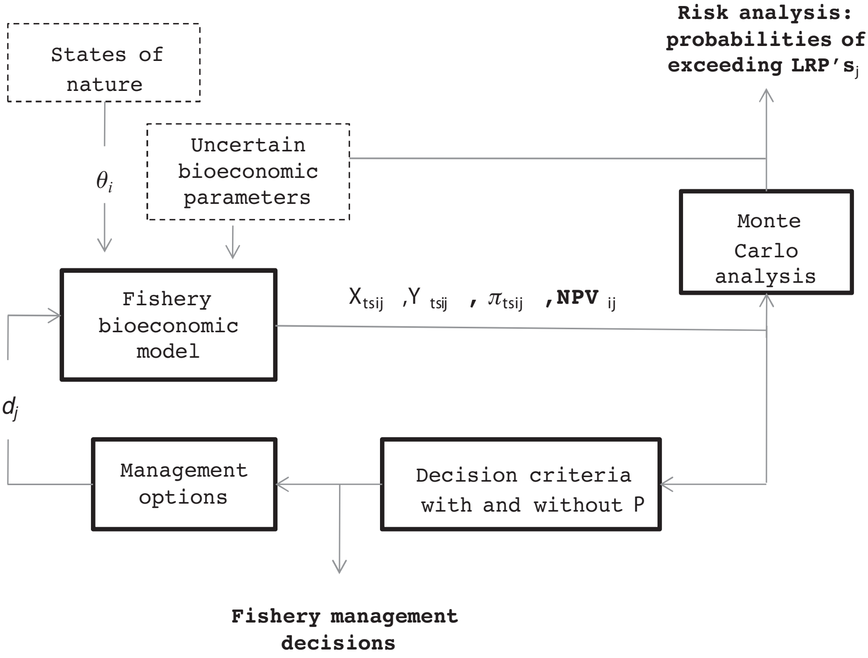

Figure 12.1 A simple bioeconomic approach for dealing with uncertainty and risk analysis in fisheries management.

9. Estimate the probabilities of exceeding limit reference points of biologic and economic indicators for the alternative management strategies under consideration.
10. Reevaluate periodically the fishery to establish new reference points and management strategies.

12.2 Indicators, reference points, and control law

For modern fisheries management, an indicator, as suggested by Garcia (1996a), is a variable, a pointer, an index of a complex phenomenon. Its fluctuations reveal the variations in components of the ecosystem, the resource, or the sector. When considered together, the position and trend of the indicator in relation to the criteria indicate the present state and dynamics of the system. *Fisheries indicators* are taken here to be variables derived from monitoring a fishery, which can assume discrete values conveying information believed to be relevant to the proper management of exploitation of the resource. Fishery and ecosystem *reference points* are considered to be discrete values of these indicators, which have been agreed to represent situations calling for prenegotiated management action. A set of fishery indicators and the reference points they can assume should be assembled into a *control law* which forms a feedback loop between incoming information on the fishery and the corresponding management response.

Fishery indicators should be able to provide information for assessing the biologic, economic, and social performance of the fishery, and as an element of the management plan, they should become an input for establishing, over time, new reference points and corresponding management strategies to achieve them. Indicators can be quite simple in conception, and can be based on semiquantitative or even qualitative information. They may need to be tuned in the light of events. They have to be integrated fully into the management system and should be sensitive indicators with the capacity of measuring dynamic change (FAO, 1999).

It should be pointed out that earlier reference points proposed by scientists have been used primarily as target reference points (TRPs), but owing to problems caused by overshooting TRPs, there has been a perceived need for reference points that help to avoid situations that are dangerous to the resource, the ecosystem, and hence, to fishery sustainability. As mentioned in Chapter 6, these have been referred to as limit reference points (LRPs), and represent fishery sustainability threshold reference points (see Caddy and Mahon, 1995). The use of limit *reference points* as constraints for resource administration represents an important step in the management process. Indicators for fishery performance are an integral part of fisheries management plans, providing dynamic signs of the relative position of such indicators with respect to the predetermined reference points. It has also been recognized that wise use of fish resources over time should incorporate the inherent risks and uncertainty in bioeconomic indicators and reference points of fishery systems (Seijo and Caddy, 2000).

Using the level, change, and structure framework proposed by Garcia (1996b), a set of sustainability indicators is suggested in Seijo and Caddy (2000).

The recognition of the uncertainty present in various parts of the fishery system is fundamental for a precautionary approach to the decision-making process. To aid this process, the use of fisheries-specific mathematical models allows researchers, managers, and resource users to experiment with different management options in order to estimate the possible dynamic consequences on different parts of the system and corresponding performance variables. Once the fishery sustainability indicators have been established with their corresponding LRPs, the next step involves estimating the probabilities of exceeding these LRPs.

In this chapter we will present two cases to illustrate the use of the approach mentioned in Figure 12.1. In case 1, the age-structured model developed in Chapter 11 for long-term fluctuating fisheries is used to estimate the bioeconomic effect of different vessel sizes to harvest a pelagic species under alternative states of nature concerning the length of cycle of the periodic fluctuation of stock biomass. In case 2, we will use an age-structured model developed in Chapter 9 to first calculate the stock recovery trajectories resulting from alternative combination of input controls and prespecified LRPs and TRPs for spawning stock biomass. The reader is invited to explore the effect of using output controls (TACs) for stock recovery when different components of the age structure of the stock are affected by minimum and maximum size restrictions.

12.3 Case 1: selecting adequate vessel size for a stock fluctuating fishery

With the parameter set and Excel spreadsheet used in Chapter 11 for age-structured model with long-term fluctuating patterns built in, we apply decision theory for systematic choice under uncertainty, considering different risk attitude criteria, with and without mathematical probabilities.

Under this approach, decision makers in fisheries are expected to select one management strategy, *d*, out of a set of *D* alternative strategies. When selecting a strategy, the fishery manager should be aware of the corresponding consequences. These consequences are likely to be a function of the cause–effect relationships specified in the fishery model, the estimated bioeconomic parameters, and the possible states of nature.

In decision theory, it is important to be able to estimate a loss of opportunities function, $L(d, \theta)$, also called *regret matrix* in the operations research literature, which reflects the resulting losses of having selected strategy *d* when the state of nature occurring is θ.

If *prior* or *posterior* probabilities are available to build decision tables for fishery managers, the expected values (EV) and their corresponding variance (VAR) should be estimated for the selected fishery performance variable, FPV, [e.g., net present value (NPV) of the fishery, spawning biomass, yield, direct employment, export earning, among others] as follows:

$$\mathrm{EV}_d = \sum_{\theta} P_\theta \, \mathrm{FPV}_{\theta,d} \tag{12.1}$$

$$\mathrm{VAR}_d = \sum_{\theta} P_\theta (\mathrm{FPV}_{\theta,d} - \mathrm{EV}_d)^2 \tag{12.2}$$

where P_θ are the probabilities associated to the different states of nature and $\mathrm{FPV}_{\theta d}$ are the values of the spawning stock biomass resulting from management decision *d* when state of nature θ occurs. A *risk-neutral* fisheries manager will select the management strategy that generates the maximum expected value with no consideration of the corresponding variance. A *risk-averse* decision maker will tend to select the fisheries management strategy that generates the minimum variance. There are, however, different degrees of risk aversion, and therefore the decision theory provides alternative criteria for increasing degrees of caution in decision making (Shotton, 1995; Shotton and Francis, 1997). Applying these concepts to fisheries, we will describe in the following section decision criteria *with* and *without* mathematical probabilities.

12.4 Bayesian criterion

The Bayesian criterion is a procedure that uses *prior* or *posterior* probabilities to aid the selection of a management strategy. It indicates the fishery manager to select the decision that minimizes the expected loss of opportunities. Decisions without experimentation use *prior* distributions estimated out of experiences that are translated subjectively into numerical probabilities. Fishery decisions that are based on experimentation can use *posterior* probabilities. Posterior probabilities are the conditional probability of state of nature θ, given the experimental data. The criterion proceeds to select the fishery management option with the lowest expected value of loss of opportunities. To this we need to build a loss of opportunities matrix, usually called regret matrix in the operations research literature.

12.5 Decision criteria without mathematical probabilities

In the absence of sufficient observations to assign probabilities to possible states of nature, there are three decision criteria reflecting different degrees of precaution concerning selection of fishery management strategies (Seijo *et al.*, 1998; Defeo and Seijo, 1999).

12.5.1 Minimax criterion

The minimax criterion estimates the maximum loss of opportunities of each management strategy and selects the one that provides the minimum of the maximum losses. This criterion proceeds as nature would select the probability distribution, defined for all possible states of nature, which is least favorable for the decision maker.

12.5.2 Maximin criterion

This criterion uses the performance variable decision table that estimates the resulting values for a set of combinations of alternative decisions and states of nature. The criterion calculates a vector of the minimum values for the performance variable resulting from each alternative management decision. Then, the fishery manager proceeds to select the maximum of the minimum of those values. This is the most cautious of the decision theory criteria.

12.5.3 Maximax criterion

A risk-prone fishery manager would tend to apply the maximax decision criterion when selecting the management strategy. The criterion calculates a vector of the maximum values for the performance variable resulting from each alternative management decision. Then, the fishery manager proceeds to select the maximum of the maximum of those values and the corresponding decision that generates it. The decision maker assumes that nature will behave most favorably to the fishery.

To illustrate the use of these alternative criteria under uncertainty, we will consider two possible lengths of cycle and amplitude of fluctuations (possible states of nature) and analyze the alternative decisions considering different selection criteria corresponding to different fishery manager attitudes toward risk.

Fisheries management in the past decades was primarily focused on maximizing economic yield (MEY) or achieving maximum sustainable yield (MSY) from the fishery by regulating fishing effort and establishing TACs and other rights-based management strategies (i.e., ITQs, comanagement, community-based management). As the effect of overfishing became more apparent in more than 70% of the world stocks, fisheries management objectives shifted from achieving MEY or MSY to maintaining a minimum spawning biomass to avoid stock collapse.

The performance variables selected for this exercise is the minimum spawning biomass (SSB_{min}) estimated in the long-term fluctuation period of the stock. The economic and biologic performance of vessels of different sizes and tonnage capacity in a fluctuating fishery is considered. Because of different unit costs of effort, the trade-offs of vessel capacity and operation costs of having sufficient capacity to harvest the resource in favorable periods need to be taken into account. For vessels not to become inactive in low biomass periods, their unit cost of effort should be covered by the relatively low revenues during unfavorable environmental conditions. The uncertainty related to the appropriate size of vessels is explored by considering possible states of nature concerning the length of the long-term environmental cycle in a systematic way using decision tables.

In Table 12.1, we have the two alternative decisions of vessel capacities where θ_1 is an environmental fluctuation cycle of 30 years and θ_2 is an environmental fluctuation cycle of 55 years. On the other hand, d_1 is a fleet with 230-ton storage capacity and d_2 is a fleet with 430 ton storage capacity.

Table 12.1 shows the minimum spawning biomass that will result in the fluctuating fishery under open access with two alternative decisions of vessel sizes (d_1 and d_2). The probabilities of occurrence of possible length of cycles, treated as uncertain states of nature in this exercise, are $P_1 = 0.3$ for state of nature θ_1 and $P_2 = 0.7$ for state of nature θ_2. With this information we can

Table 12.1 Performance values (minimum spawning biomass '000 ton) of fishery under different states of nature and management decisions.

Decision (d_j)	**States of nature (θ_i)**		**EV**	**VAR**
	θ_1 ($P_1 = 0.3$)	**θ_2 ($P_2 = 0.7$)**		
d_1	673	918	845	12,605
d_2	420	1,202	967	128,420

Table 12.2 Loss of opportunity matrix with mathematical probabilities for the Bayesian criterion.

Decision (d_j)	**States of nature (θ_i)**		**EV**
	θ_1 ($P_1 = 0.3$)	θ_2 ($P_2 = 0.7$)	
d_1	673 – 673 = 0	1202 – 918 = 284	199
$\boldsymbol{d}_2$	673 – 420 = 253	1202 – 1202 =0	**76**

estimate the loss of opportunity matrix, as shown in Table 12.2. The values indicate the loss of opportunities of choosing d_1 or d_2 when each state of nature occurs. The purpose is to determine which vessel size is more appropriate in terms of the effect on the minimum level of spawning biomass in the fluctuating fishery when possible states of nature of length of cycle may occur.

The Bayesian criterion selects the decision of vessel size that causes the minimum expected losses of opportunity. In this case, decision d_2 applies.

In the absence of sufficient observations to estimate probabilities for the two different cycles under consideration, we can have a decision table without mathematical probabilities using the loss of opportunities matrix and apply the minimax criterion that selects the decision that provides the minimum of the maximum losses (Table 12.3). We can see that this criteria provide a consistent result with the one obtained with the Bayesian approach.

An additional criterion without probabilities is called the maximim criterion. It uses the performance values for the variable of interest of Table 12.1, to calculate a vector of minimum spawning stock biomass in this case, to select the decision that provides the maximum of the minimum performance estimated. Therefore, d_1 from the vector min of Table 12.4 is selected.

This criterion is more cautious than the Bayesian and the minimax criterion. The three criteria discussed reflect different degrees of risk aversion. The reader can use the chapter models to explore other uncertain bioecological parameters and build the corresponding decision tables with and without mathematical probabilities. Likewise, from a fishery management perspective, decisions concerning input controls, like the ones explored in this chapter, or output controls (alternative TACs over time, as suggested in the exercises of this chapter) can be explored as alternative decisions in the context of possible states of nature of global oceanic patterns determing the fluctuation of the fishery.

Table 12.3 Loss of opportunity matrix without mathematical probabilities for the minimax criterion.

Decision (d_j)	**States of nature (θ_i)**		**MAX**
	θ_1	θ_2	
d_1	0	284	284
$\boldsymbol{d}_2$	253	0	**253**

Table 12.4 Loss of opportunity matrix without mathematical probabilities for the maximin criterion.

Decision (d_j)	States of nature (θ_i)		MIN
	θ_1	θ_2	
$\boldsymbol{d_1}$	673	918	**673**
d_2	420	1,202	420

12.6 Case 2: stock recovery strategies of a multifleet fishery with alternative biomass LRPs

Many of today's developed fisheries already have overcapacity, and therefore usually managers are concerned about protecting juveniles as well as the spawning stock from being harvested in overexploited fisheries (Caddy and Seijo, 2002). Nevertheless, size restrictions can be meaningless if fishing effort or fishing mortality is not controlled. Therefore, one can ask the management question for the case of protecting juveniles in two ways: (1) What is the minimum size restriction that will maximize NPV for a given level of fishing effort? or (2) What is the level of fishing effort that will maximize NPV for a given minimum size restriction. Also, given the species' life cycle and corresponding population renewability capacity, fisheries biologists can indicate the spawning biomass level below which the sustainability of the fishery can be threatened. This can be expressed in terms of a proportion of final over initial spawning stock biomass (SSB_{max}). This ratio constitutes an LRP. Depending on species' biological/ecological characteristics, one can explore the stock recovery trajectory prespecifying LRPs for the spawning biomass ratio mentioned above (e.g., $LRP_1 = 0.3SSB$, $LRP_2 = 0.4SSB$) as well as TRPs for this variable (e.g., $TRP = 0.5SSB$).

Using an age-structured bioeconomic model with parameter set of Table 12.5, we can, for stock recovery purposes, determine the level of fishing mortality for different possibilities of minimum or maximum size restriction to comply with a biologically prespecified limit reference point for spawning biomass in an overexploited fishery. We can also estimate the risk of exceeding biologic and economic LRPs with alternative effort/minimum size combinations.

For the determination of the optimum effort, the model should be run without Smith's effort dynamics function. The optimizer generates an effort level that is then assumed constant for the full simulation period, and finally selects the one that generates the maximum NPV for a given rate of discount. The effort level that maximizes the NPV will vary depending on the rate of discount used. It is suggested to explore results with different rates of discount that reflect different prices of time.

The LRP for spawning biomass is introduced as a functional constraint that needs to be satisfied (e.g., $LRP \geq 0.3$, meaning that final spawning biomass should be equal to or greater than 30% of the estimated initial spawning biomass).

Table 12.5 Bioeconomic parameter set for the age-structured fishery.

Parameter	Symbol	Value	Unit of measurement
Natural mortality	M	0.21	1/year
Parameter for mortality reciprocal function	α_1	0.1416	–
Parameter for mortality reciprocal function	β_1	0.8	–
Initial recruitment	R	55,000,000	1/year
B-H recruitment parameter	α_2	55,000,000	individuals
B-H recruitment parameter	β_2	55690	individuals
Fishing mortality coefficient	F	0.18	1/year
Maximum length of species	L^∞	92	cm
Growth parameter	k	0.18	1/year
Length–weight parameter	α_3	0.013	g
Exponent of length–weight relationship	β_3	3.0546	g
Price of species	p	5,000	US$/ton
Unit cost of effort	cu_i	25,000	US$/vessels/year
Entry–exit parameter	ϕ	0.0001	vessels/US$
Rate of discount	d	0.05	1/year
Area swept per day	A	2.7	km^2/vessel/year
Area of resource distribution	area	7600	km^2
Length at 50% gear retention	$L_{50\%}$	45	cm
Length at 75% gear retention	$L_{75\%}$	65	cm
Parameter for selectivity curve	S_{1i}	2.47	–
Parameter for selectivity curve	S_{2i}	0.05	–
Probability of capture	c	0.90	

In Figure 12.2, we can see optimum levels of fishing mortality that will result for given alternative minimum size restrictions and corresponding LRP for spawning biomass. With the smaller LRP (e.g., LRP = 0.3SSB), the fishery will be at bioeconomic optimum (maximum NPV) with the highest levels of fishing mortality. The larger the proportion of final to initial spawning biomass that is prespecified as LRP, the smaller the fishing mortality level that should be applied to maximize NPV for alternative minimum size restrictions.

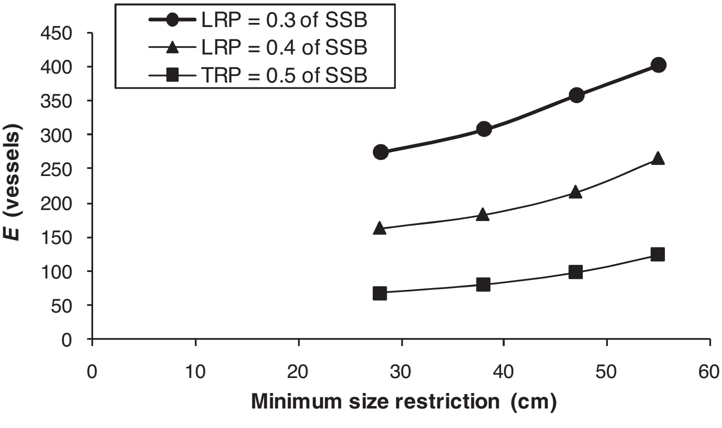

Figure 12.2 Optimum levels of effort (E), given minimum size restriction and LRP = 0.3 for spawning biomass.

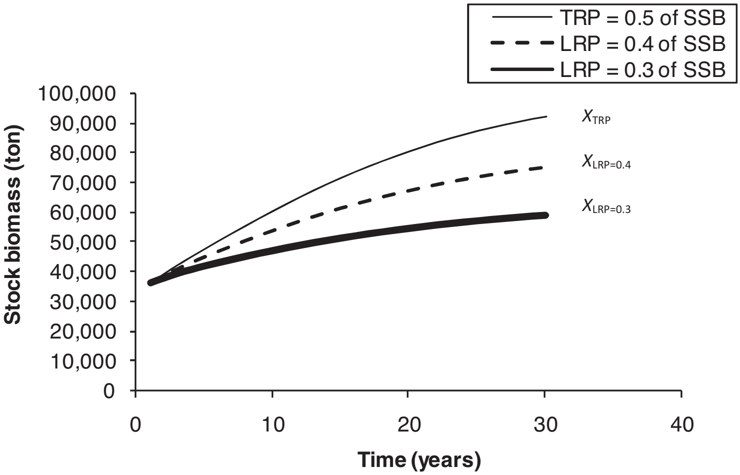

Figure 12.3 Dynamic recovery trajectory under three alternative LRPs.

For two different LRPs for spawning stock biomass (LRP = 0.3SSB, LRP = 0.4SSB) and a TRP = 0.5SSB, different combinations of minimum size restriction and vessels are needed to maximize the NPV of the fishery.

On the other hand, the stock recovery trajectories over time for given alternative prespecified LRPs and TRPs for spawning stock are presented in Figure 12.3. This figure shows the dynamic trajectory from the status quo overexploited stock biomass, $X_t = 0$, to the two alternative LRPs and a TRP established for a hypothetical fishery targeting a long-lived fish species.

To illustrate the change in the age structure of the population, resulting from the stock recovery strategy having input controls (effort and minimum size restriction), Figures 12.4 and 12.5 show the change in age-specific biomass and catch from status quo (overexploited fishery in t_0) to the one resulting after the stock recovery period in t_{30}.

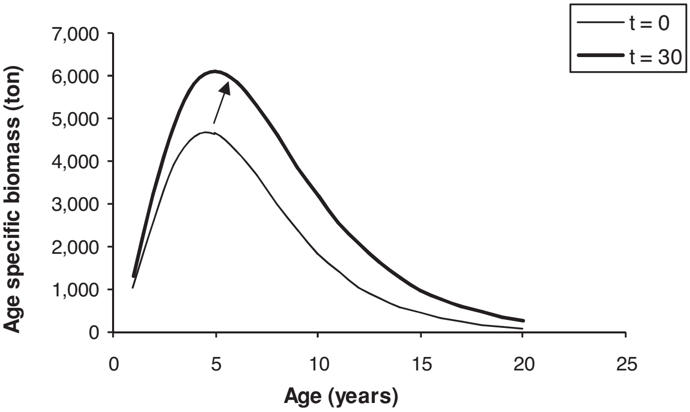

Figure 12.4 Age structure effect of stock recovery.

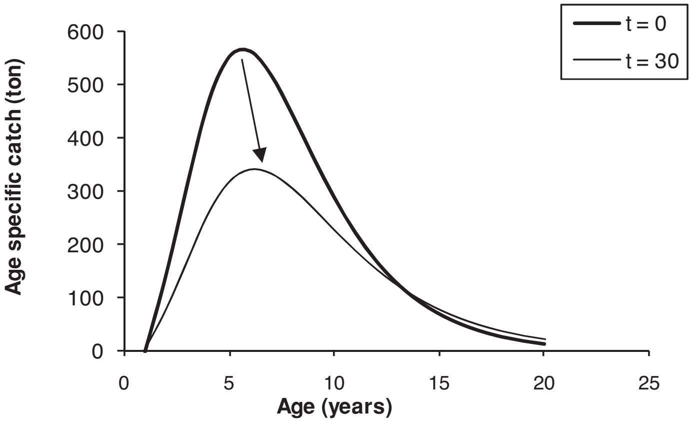

Figure 12.5 Age-specific catch effect of optimizing fishing capacity and satisfying a spawning biomass LRP.

It should be pointed out that stock recovery trajectories using other input controls as well as output controls (TACs) can be explored considering the set of regulatory options presented in the comprehensive fishery regulation framework discussed in Chapter 7.

In the exercises of Chapter 12 given in the CD, the model used for the case just described is prepared for the reader to explore alternative stock recovery strategies.

As acknowledged at the beginning of this chapter, there are growing sources of uncertainty in marine fisheries resulting from climate change and other factors, including anthropogenic ones, which may prevent the fishery from arriving to the target stock biomass and/or to be above a prespecified LRP for relevant biological and economic variables of the fishery. Hence, we have to move from the deterministic stock recovery process just described and shown above to a stochastic one where we are interested in estimating the risks of exceeding prespecified critical LRP such as spawning biomass.

12.7 Probability of exceeding a spawning stock LRP in the stock recovery process

In the stock recovery process, there can be sources of variability of critical age-structured parameters such as age-specific natural mortality and recruitment of new individuals to the population. As shown in the previous sections of this chapter, with the use of Monte Carlo analysis we can calculate the probability of exceeding a spawning stock prespecified LRP as a result of, for instance, changes in the age-specific pattern of natural mortality. By generating random variables for parameter α in Caddy's reciprocal age-specific natural mortality equation, we obtain a distribution for possible ratios of SSB_T/SSB_{max}, and estimate the area in the distribution that falls below a prespecified LRP for spawning stock biomass such as $LRP = 0.3SSB$. This is shown in Figure 12.6.

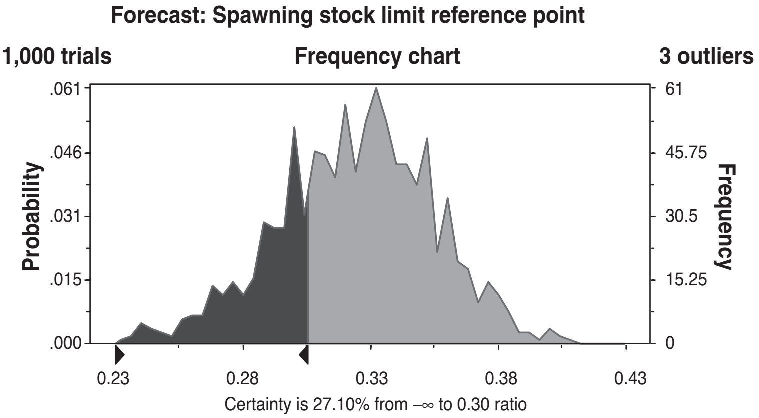

Figure 12.6 Risk of exceeding LRP when age-specific natural mortality is randomly varying.

In this figure, after generating 1,000 values for parameter α, we calculate the risk (dark area under the probability distribution chart, 27.1%) of having spawning stock biomass falling below a prespecified LRP = 0.3SSB.

With this risk information, the decision maker and his inherent attitude toward risk will determine whether the input and/or output controls in place should be expanded or not to reduce risks in the fishery stock recovery process.

It should be pointed out that the Monte Carlo analysis to estimate the probabilities of exceeding LRPs and the use of decision tables with and without mathematical probabilities to deal with uncertainty in fisheries can be applied to any of the models developed in the previous chapters of this book.

The reader is invited to explore the complexities of stock recovery processes in a multifleet fishery context using the Excel model of Chapter 9 given in the exercises CD included in the book.

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Appendix 1

Spatial dynamics of the fishery for three possible strategies of spatial behavior of fishers

This appendix presents three possible representations of spatial behavior of fishers: (1) spatial allocation proportional to abundance, (2) spatial fishing intensity based on quasi profits of the variable costs obtained from alternative fishing grounds in previous trips, and (3) spatial fishing intensity as a function of quasi profits of variable costs and friction of distance (to account for nonmonetary costs associated to distance between port of origin and alternative fishing grounds).

Using the Excel model developed for this chapter, we can observe that a spatial fishing strategy proportional to abundance will result in the lowest biomass level (X_3 in Figure A1.1a). This is so because the allocation assumption of perfect information, without relevance of the corresponding transfer costs to different sites, makes the stock more vulnerable than the other two assumptions behind the spatial allocation strategy.

Concerning fishery yield, the dynamic trajectories of the three spatial allocation strategies are shown in Figure A1.1b. With the perfect information assumption of the proportional to abundance allocation strategy, yield tends to grow faster than with the other two effort allocation strategies. This is consistent with what we observe in Figure A1.1a, where biomass decreases faster when the proportional allocation strategy is considered.

Dynamic profits of the three strategies are shown in Figure A1.1c. A spatial fishing intensity strategy based on the quasi profits obtained in alternative fishing sites will initially yield higher profits than the proportional allocation strategy, causing a grater entry rate of vessels to the fishery. This is so because profits are greater with this strategy that accounts for not only the relative stock abundance over space, but also the steaming cost of going from port to alternative fishing sites when spatially allocating effort.

Therefore, initially this strategy drives down biomass faster but eventually will reach a bioeconomic equilibrium at a higher biomass level than with proportional allocation to abundance.

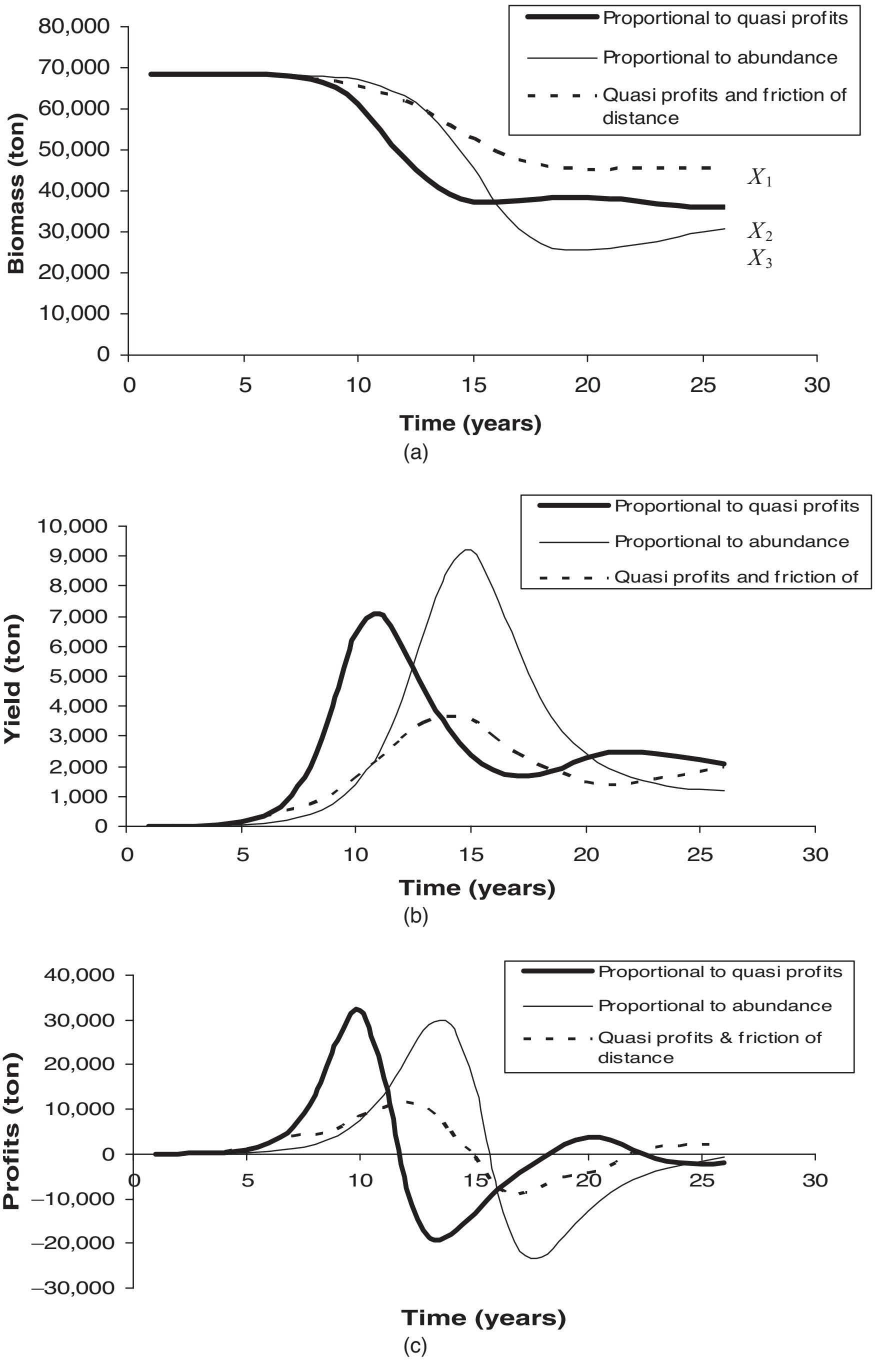
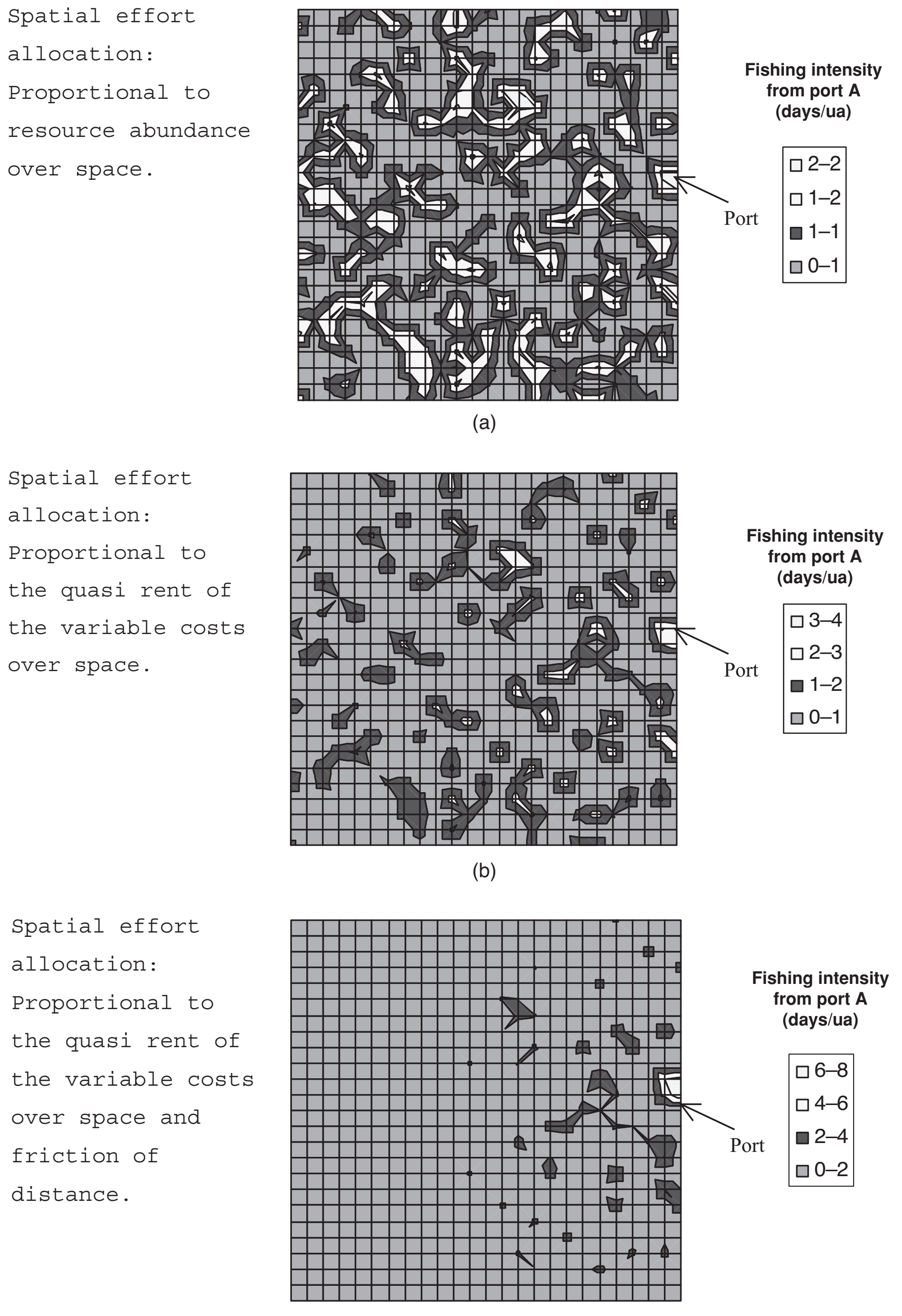


Figure A1.1 Dynamic open access bioeconomic performance of assuming alternative spatial behavior of fishers.



(a)

(b)

(c)

Figure A1.2 Spatial distribution of fishing intensity for three possible representations of spatial behavior of fishers.

When the friction of distance (nonmonetary cost associated to distance traveled in the specific vessel and fishing area) is relevant to the fishery in question (representation 3 above), this will cause vessels to fish closer to port than the other two alternative options, allowing more spawning biomass located in distant waters to remain unharvested for the next spawning period.

In Figure A1.2, we can observe the spatial distribution of fishing intensity of the three possible representations discussed previously. With spatial allocation of effort proportional to stock abundance over space, we can see that effort is distributed all over the area (Figure A1.2a). On the other hand, when the transfer costs become relevant and the allocation strategy is proportional to the quasi rent of the variable costs over space, fishing days tend to be allocated more toward the port of origin (Figure A1.2b). Finally, when the friction of distance is added to previous case, effort tends to remain in fishing areas close to the fishing port (Figure A1.2c).

Appendix 2

Modeling recruitment seasonality

Modeling recruitment seasonality using the distributed delay model is based on the Erlang family of probability density functions (Equation A2.1):

$$E(t; D, k) = \frac{(g/D)^g t^{g-1}\, e^{-gt/D}}{(g-1)!} \tag{A2.1}$$

where D is the mean development or maturation period and g (an integer) specifies the member of the family of Erlang functions.

$$\frac{dR_1}{dt} = \frac{g}{D}(pl_{i,t} - R_{1,t}) \tag{A2.2}$$

$$\frac{dR_2}{dt} = \frac{g}{D}(R_{i,t} - R_{2,t}) \tag{A2.3}$$

$$\frac{dR_g}{dt} = \frac{g}{D}(R_{g-i,t} - R_{g,t}) \tag{A2.4}$$

where pl is postlarvae recruiting to the area, $R_{g,t}$ is recruits to age 1, $R_{1,t}$, $R_{2,t}$, … , $R_{g,t}$ are the intermediate rates of the delay process used to represent the distribution of seasonal recruitment, D is average maturation/development time, and g is order of the distributed delay, representing the member of Erlang family of density functions.

Solving the above-mentioned set of differential equations using Euler numerical integration, we have:

$$R_{1,t+dt} = R_{1,t} + DT\left[\frac{g}{D}(pl_{i,t} - R_{1,t})\right] \tag{A2.5}$$

$$R_{2,t+dt} = R_{2,t} + DT\left[\frac{g}{D}(R_{1,t} - R_{2,t})\right] \tag{A2.6}$$

$$R_{g,t+dt} = R_{g,t} + DT\left[\frac{g}{D}(R_{g-1,t} - R_{g,t})\right] \tag{A2.7}$$

Appendix 3

Summary of model equations and bioeconomic parameter sets

Table A3.1 Summary of equations used in the seasonal and medium-term age-structured bioeconomic model.

Equation	Description	Unit
$R_t = \dfrac{\alpha\,\mathrm{SSB}_t}{\beta + \mathrm{SSB}_t}$	Beverton–Holt recruitment function	individuals
$N_{i+1,t+1} = N_{i,t}e^{-(M+\sum\limits_{m} F_{i,m,t})}$	Dynamic population structure over time	individuals
$X_{i,t} = N_{i,t}W_i$	Age-specific biomass	ton
$F_{i,m,t} = E_{m,t}q_{i,m}$	Age-specific fishing mortality of fleet *m*	
$C_{i,m,t} = \left[\frac{F_{i,m,t}}{F_{i,m,t}+M_i}\right]\left[1 - e^{-(F_{i,m,t}+M_i)}\right] X_{i,t}$	Age-specific catch in time *t*	ton
$C_{m,t} = \sum\limits_{i=1}^{i=\max age} C_{i,m,t}$	Total catch of fleet *m*	ton
$TR_{m,t} = \sum\limits_{i} C_{i,m,t}\,pi$	Total revenue of fleet *m*	US$
$\Pi_{m,t} = TR_{m,t} - TC_{m,t}$	Profits of fleet *m* over time	US$
$V_{m,t+DT} = V_{m,t} + \int\limits_{t}^{t+DT} (\phi\pi_{m,t})\,dt$	Number of vessels type *m*	vessels

Table A3.2 Parameter set for the age-structured bioeconomic model with seasonality.

Parameters	Symbol	Value	Unit
Growth parameter	k	0.25	1/fortnight
Natural mortality coefficient	M	0.005	1/fortnight
Maximum weight of species	W_i	2,000	g
Maximum length of species	L_i	220	mm

(Continued)

Table A3.2 (*Continued*)

Parameters	Symbol	Value	Unit
Parameter of growth equation	t_0	0.2	fortnight
Unit cost of effort: industrial fleet	c_1	1,856	US$/vessel/day
Unit cost of effort: small-scale fleet	c_2	450	US$/vessel/day
Length at 50% gear retention: small-scale fleet	$L_{50,\mathrm{sc}}$	120	mm
Length at 75% gear retention: small-scale fleet	$L_{75,\mathrm{sc}}$	170	mm
Selectivity parameter: small-scale fleet	S_1	1.145091011	–
Selectivity parameter: small-scale fleet	S_2	0.009542425	–
Length at 50% gear retention: industrial fleet	$L_{50,\mathrm{ind}}$	170	mm
Length at 75% gear retention: industrial fleet	$L_{75,\mathrm{ind}}$	180	mm
Selectivity parameter: industrial fleet	S_1	8.11106133	–
Selectivity parameter: industrial fleet	S_2	0.047712125	–
Catchability coefficient: small-scale fleet	q_1	0.00001	1/vessel
Catchability coefficient: industrial fleet	q_2	0.00002	1/vessel
Alpha weight–length relationship parameter	α	0.00000975	g
Beta weight–length relationship parameter	β	3.1222	–
Exit–entry parameter	ϕ	0.0000001	Vessels/US$

Table A3.3 Seasonality parameters for spawning, hatching, and recruitment processes.

Distributed delay parameters	Spawning	Hatching	Recruitment
Average biological period	5	5	4
Order of the distributed delay	3	3	3

Table A3.4 Parameter set for the fluctuating fisheries: age-structured model.

Parameters	Symbol	Units	Value
Natural mortality	M	1/year	0.5
Initial recruitment	R_0	1/year	9×10^{11}
Maximum length	L_∞	cm	20.1
Growth	k	1/year	0.36
Parameter of length–weight relationship	a	g	0.004
Parameter of length–weight relationship	b	g	3.0546
Price of species	p	US$/ton	5,000
Unit cost of effort: industrial fleet	c_1	US$/vessel/year	410,000
Unit cost of effort: artisanal fleet	c_2	US$/vessel/year	220,000
Fleet dynamics parameter: industrial fleet	ϕ_1	vessels/US$	0.0000009
Fleet dynamics parameter: artisanal fleet	ϕ_2	vessels/US$	0.0000009
Area swept: industrial vessel	α_1	km^2/vessel/year	30
Area swept: artisanal vessel	α_2	km^2/vessel/year	5
Area of resource distribution	area	km^2	7,600
Length at 50% gear retention: industrial	$L_{50\%\ 1}$	cm	15
Length at 50% gear retention: artisanal	$L_{50\%\ 2}$	cm	10
Length at 75% gear retention: industrial	$L_{75\%\ 1}$	cm	17
Length at 75% gear retention: artisanal	$L_{75\%\ 2}$	cm	12
Parameter selectivity equation: industrial	$\underline{S}_{1i}$	–	8.24

Table A3.4 (*Continued*)

Parameters	Symbol	Units	Value
Parameter selectivity equation: artisanal	S_{1a}	–	5.49
Parameter selectivity equation: industrial	S_{2i}	–	0.55
Parameter selectivity equation: artisanal	S_{2a}	–	0.55
Probability of capture	c		0.90
Parameter a_1 of Ricker curve with environment fluctuation	φ_1	–	12.4
Density-dependent parameter b_1 of Ricker curve	φ_2	–	1.00318×10^{-7}
Parameter c_1 of Ricker curve with environment fluctuation	φ_3	–	0.6
Average temperature	AT	°C	18.2
Amplitude of sine function	σ_{temp}	°C	1.41
Environmental cycle	cycle	years	55

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