

CHAPTER 1

A GENERIC BIOECONOMIC MODEL

1.1 WHAT IS CONSERVATION?

As a prelude to studying this book it might be worthwhile taking a look at S.V. Ciriacy-Wantrup's 1972 book "Resource Conservation: Economics and Policies." In discussing the meaning of conservation, Ciriacy-Wantrup points out that

1. Conservation does not mean non-use;
2. Certain popular definitions of conservation, such as "the wise use of resources," or "the greatest use to the greatest number over the greatest time" are meaningless and of no use for economic analysis;
3. The essence of conservation is its dynamic, time-dependent aspect.

The dynamic nature of resource conservation is a *leitmotiv* of the present book. Analyses of resource management that are not explicitly dynamic are misleading, even dangerous. The same can be said of discussions of resource management that exclude economic aspects. This chapter, like the rest of the book, formulates and analyzes dynamic economic models of biologically renewable resources.

Roughly speaking, conservation means saving for the future. Saving is a form of investment. The theory of resource conservation can therefore be addressed as a branch of the theory of capital and investment. A given resource stock, such as a mineral deposit, a forest, or a population of fish, is a capital asset – natural capital if you like (Jansson et al. 1994).

An exploitation strategy specifies the rate of removals (harvests) over time. Each such strategy also determines the remaining stock over time. A strategy that retains a higher future stock level than some other strategy would be considered the more conservationist of the two.

In assessing the relative advantages of alternative exploitation strategies, clearly more is involved than their relative conservation ratings, however. The costs and benefits of harvesting, for example, also need to be considered. In many cases external effects on other resource stocks may also be important – an example being a fish population that preys upon, or is preyed upon by, another population.

Is it possible, then, to specify an *optimal* exploitation strategy for a given resource stock? This important question is studied later in this chapter, and throughout the book. (We treat only renewable resources, referring the reader to the existing literature on exhaustible resource economics; see e.g., Solow 1974, Conrad and Clark 1987.

“Optimal” is a loaded word. It is important to realize that what strategy is deemed optimal depends entirely on one’s specification of an objective function. The objective function normally used in cost-benefit analysis is the discounted present value of future net economic gains (Mishan and Quah 2007). As Ciriacy-Wantrup (1972) pointed out, in the setting of resource economics the optimal exploitation strategy is often strongly affected by the assumed rate of discount. This should be no surprise, because discount (i.e., interest) rates are of over-riding importance in investment decisions generally. The question of an appropriate discount rate for social cost-benefit analysis is complex and controversial (Arrow and Kurz 1970). Both the private sector and the government sector use discounting in development and investment decisions. If, as often asserted, private discount rates tend to be large, the conclusion is that resource exploitation strategies preferred by individuals and firms may be far from conservationist. We discuss the role of discounting throughout the book.

Open-access resources

Many natural resources are exploited under conditions of open-access. Examples include fisheries, wildlife, and on a larger scale, the oceans and the atmosphere. Unless specific institutions exist to control the exploitation of these resources, the inevitable outcome is over-exploitation – just the opposite of conservation. How to overcome this problem, especially in the case of international resource stocks, is far from obvious. But even for resources under the jurisdiction of a single state (or a small number of neighbouring states) achieving sustainable and profitable use patterns for biological resources has sometimes been difficult. The models discussed

in this book can indicate why this is so, and can suggest what management techniques are likely to be successful.

1.2 WHAT IS A MODEL?

Models come in every size and form, from verbal descriptions and mathematical equations to large-scale computer models. One feature common to all models in the life and social sciences is that they constitute abstractions and simplifications of the real world. Indeed, any model that merely duplicated reality (if such were possible) would be all but useless, at least in terms of providing insights.

Although desirable and inevitable, model simplicity comes with a cost – namely, the model may turn out to be seriously flawed in some respects. A well-chosen model may provide a satisfying or convincing explanation for some phenomenon, but nevertheless be seriously misleading in other ways. The danger is that such a model will become uncritically accepted in applications for which it is not appropriate (Daly and Cobb 1989). *Every modeler therefore has an obligation to think about and publicize the underlying assumptions and limitations of his or her model.* This principle of model criticism surfaces throughout the book. Some readers may consider this approach too indecisive – you should choose your model carefully, but then stick with it. While it is certainly possible to overdo the questioning of model assumptions, the position taken here is that because resource systems are usually highly complex, simplified models are inevitable, but these models will almost always have significant limitations. A given model may lead to unanticipated predictions, or to novel explanations of mysterious observations. If so, the model is successful as an aid to understanding – provided that the predictions are reasonably robust, meaning that they do not critically depend on assumptions that may be dubious.

How does one determine which model is best in a given situation? To answer this, we first need to know whether the required model is qualitative or quantitative. For quantitative models – for example, if the model is to be used to generate a quantitative resource harvesting strategy – then model choice should be determined by the available data (Hilborn and Mangel 1997). For qualitative models, on the other hand, the best approach will often be to develop several alternative models, so as to throw light on different aspects of the problem. Many examples of this approach occur throughout the book.

Although quantitative models are obviously necessary in resource management, the value of qualitative models should not be overlooked. For example, a quantitative model may be used to calculate a desirable annual catch quota for a certain fishery, but this model will not predict how the fishermen are likely to react to setting such a quota. A qualitative behavioral model can, however, provide such predictions. The model may indicate that fishermen's behavior can strongly affect the success of any management program. We discuss this point at length later in this chapter.

Computer models

The reader will perceive that there are no computer models in this book. Computer models are widely used to simulate the dynamics of exploited populations and ecosystems; such simulation studies are essential in specific cases. But computer simulation models are usually less effective at providing insights and general principles than are analytic models. Unlike computer models, analytic models can be fully understood in detail. The role of each model assumption can be studied by investigating the predictions of alternative models. (Of course, sensitivity studies can and should be performed with computer models as well. But understanding sensitivity results is difficult without any prior experience from analytic, or “theoretical” models.)

It could be even be said that analytic models meet the basic scientific requirement of being reproducible and testable. Anyone can replicate and study an analytic model and its alternatives. This is simply not the case for most simulation models. One must remain skeptical in the face of claims that “our model shows that . . . ,” when such claims cannot be verified independently. The epithet “junk science” is perhaps not too extreme for such modeling exercises. See Hilborn and Mangel (1997) for an invigorating study of model criticism and evaluation. And for computer-oriented exercises based on simple bioeconomic models see Conrad and Clark (1987) and Conrad (1999).

EXERCISES

- 1.1 a)** Without looking ahead in the book, try to develop a model for the optimal age at which to log a tree-farm site consisting of trees of uniform age. Take account of the fact that after logging, the site will be re-planted.
- b)** What are the main assumptions of your model? What data would be needed to make it operational?

1.2 The minimum legal size of lobsters caught in Maine is regulated by the state. Develop a model to determine the optimal minimum size limit. Assume that the recruitment of young lobsters is exogenous, for example because of an unfished offshore breeding population. Discuss the limitations of your model. (The size limit for lobsters in Maine is highly controversial – see Corson 2005.)

1.3 A DYNAMIC RESOURCE-HARVESTING MODEL

We now describe a basic model of renewable resource exploitation. This model is sometimes used in fisheries (Clark 2006), and we will adopt that framework. Many of the model’s predictions are also pertinent to other resources, however.

Here is the model:

$$\frac{dx}{dt} = G(x) - h(t), \quad t \geq 0 \quad (1.1)$$

$$x(0) = x_0 \quad (1.2)$$

Here $x = x(t)$ denotes the size (e.g., biomass, in tonnes) of the fish stock at time t . Time units are specified according to convenience, say years. The initial population size, at $t = 0$, is denoted by x_0 . Equation (1.1) is sometimes referred to as a *general production* model, emphasizing that it does not involve any structure of the resource, such as the age of individuals or the spatial distribution of the population.

The function $G(x)$ in Eq. (1.1) represents the net natural growth rate of the population biomass, in tonnes/yr, depending on its current size x . (Already we see a significant abstraction, in that population growth typically involves at least three processes – birth, death and individual growth. Models that incorporate these processes are discussed in Chapter 6.)

Finally, the function $h(t)$ in Eq. (1.1) denotes the rate of removals, or harvest, of the resource stock at time t . If the harvest rate also depends on x , we write $h(x, t)$ instead of $h(t)$, in Eq. (1.1).

For obvious reasons, we stipulate that

$$x(t) \geq 0 \text{ and } h(t) \geq 0 \quad (1.3)$$

Note that if the functions $G(x)$ and $h(t)$ are given, then the differential equation (1.1) together with the initial condition (1.2) determines the stock size $x(t)$ for all future time t . Among possible harvest strategies $h(t)$ there are *sustainable* and non-sustainable strategies. Sustainable harvesting in this setting means that a certain constant harvest rate $h_0 > 0$ is sustained indefinitely (although the initial rate $h(t)$ may differ from h_0). It is also possible to determine “optimal” harvest strategies under various assumptions, as we shall see. Finally, we can add a behavioral component for resource exploiters (fishermen), and predict the outcome under various conditions.

The natural growth function $G(x)$ is assumed to satisfy

$$G(x) > 0 \text{ for } 0 < x < K \quad (1.4)$$

$$G(0) = G(K) = 0 \quad (1.5)$$

$$G''(x) < 0 \text{ for } 0 < x < K \quad (1.6)$$

An example is shown in Figure 1.1. The stock level K is called the *carrying capacity* for the given population. This term reflects the fact that if $h(t) \equiv 0$ then

$$\lim_{t \rightarrow \infty} x(t) = K \quad (1.7)$$

In other words, the point $x = K$ is a *stable equilibrium* for the unharvested population. (We do not consider the case $x_0 > K$, assuming that this would never occur under natural conditions. Mathematically, however, we could prescribe that $G(x) < 0$ for $x > K$, in which case Eq. (1.7) is valid for any $x_0 > 0$.)

Note also that $x = 0$ is an *unstable equilibrium* for the unharvested population, since $dx/dt > 0$ for small $x > 0$ (when $h = 0$). Thus our model assumes that if harvesting ceases, the population will necessarily recover over time, from any level of depletion that does not actually remove the last member of the population.

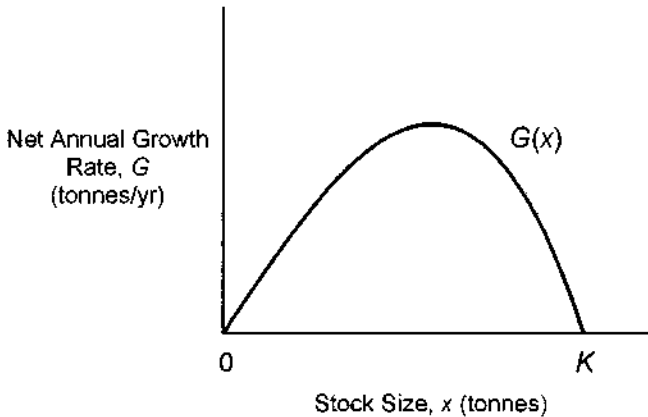


Figure 1.1 The growth function $G(x)$ of the basic (general production) biological model.

As was pointed out in the preceding section, it is important to specifically recognize built-in, or tacit, model assumptions. Although I will not be itemizing blunders from the literature that have resulted from a failure to recognize a model's built-in assumptions, I can assure you that such errors are commonplace. In building your own models, or in reading someone else's, it is essential that you recognize the underlying assumptions. It may be worthwhile to pause here and make for yourself a mental list of obvious assumptions behind the general production model. Some examples: single-species unstructured population; constant parameters; deterministic; no seasonal variation; etc.

Before proceeding, let us ask whether Eq. (1.1), in spite of some shortcomings, is in any way reasonable as a model of population dynamics. You are no doubt familiar with the equation for exponential growth

$$\frac{dx}{dt} = rx, \quad x(0) = x_0 \quad (1.8)$$

This has the unique solution

$$x(t) = x_0 e^{rt} \quad (1.9)$$

i.e., exponential growth. For obvious reasons, this model is not reasonable for actual populations, at least over long time spans. Eventually, when the population gets large enough, environmental constraints must take over and inhibit further increases in population size.

Ecologists refer to Eq. (1.8) as a model of *density-independent* population growth. Our harvest-free resource model,

$$\frac{dx}{dt} = G(x), \quad x(0) = x_0 \quad (1.10)$$

is said to describe population growth under *density dependence* (May 1981; Walters and Martell 2004). Given that $G(x)$ satisfies Eqs. (1.4)-(1.6), we see that the

population size is constrained by the carrying capacity K , as in Eq. (1.7). In this sense at least, our model is somewhat biologically reasonable.

Since $G(0) = 0$, we have, for small x (by Taylor's theorem)

$$G(x) \simeq rx \quad \text{where } r = G'(0) \quad (1.11)$$

Thus if the initial population is small, $x_0 \ll K$, then population growth is initially approximately exponential. Figure 1.2 illustrates this feature. The number r is called the *intrinsic growth rate* of the population.

Do real populations in the wild behave like this? Not exactly of course, but if a population is to persist over long periods of time without either becoming extinct or growing indefinitely large, some mechanism of population regulation must exist. Also, any population capable of providing long-term sustained harvests must be capable of self-replacement. Our general production model has these desirable features. Still, we must keep in mind that predictions obtained from the model might be of dubious value. With these reservations we will continue to use the biological model of Eq. (1.10) for now.

The logistic model

The following functional form for $G(x)$ is called the *logistic* model:

$$G(x) = rx \left(1 - \frac{x}{K}\right) \quad (1.12)$$

In this case Eq. (1.10) can be solved explicitly by separation of variables. Write Eq. (1.10) in the form

$$\frac{dx}{x(K-x)} = \frac{r}{K} dt$$

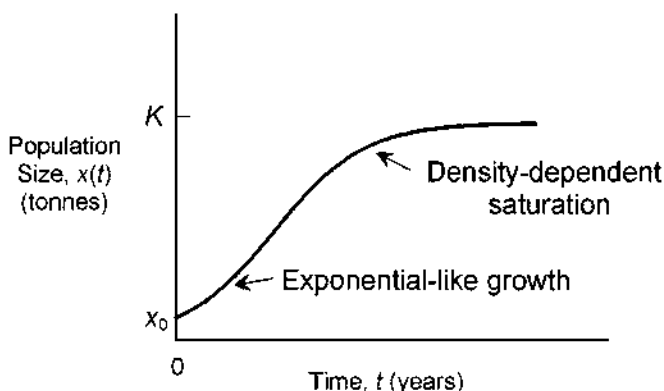


Figure 1.2 Population trajectory $x(t)$ for Eq. (1.10) with small initial population x_0 . The population initially increases approximately exponentially, but eventually levels off as a result of density dependence.

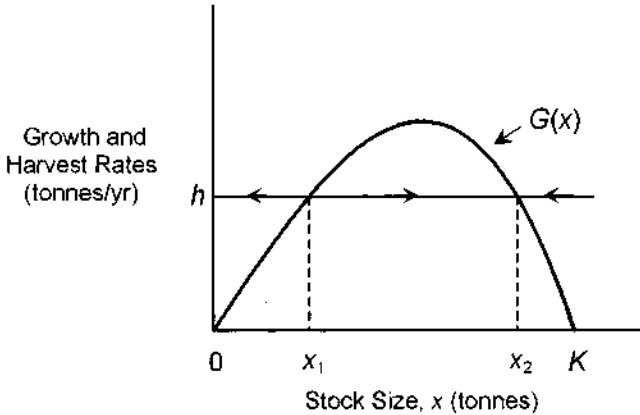


Figure 1.3 Constant-rate harvest dynamics, Eq. (1.14). There are two equilibrium points, x_1 (unstable) and x_2 (stable). Arrows indicate direction of change of x .

Hence

$$\int_{x_0}^x \frac{dx}{x(K-x)} = \int_0^t \frac{r dt}{K}$$

from which we obtain

$$\ln \frac{x}{K-x} = rt + \ln \frac{x_0}{K-x_0}$$

The solution can be written in the form

$$x(t) = \frac{K}{1 + ce^{-rt}} \quad \text{where } c = \frac{K-x_0}{x_0} \tag{1.13}$$

This is the curve illustrated in Fig. 1.2.

Maximum sustained yield

Simple as our model may be, it is in fact the basis for a widely accepted resource-management prescription called *Maximum Sustained Yield*, or MSY. Consider Eq. (1.1) again, but now suppose that $h(t) = h = \text{constant}$:

$$\frac{dx}{dt} = G(x) - h, \quad x(0) = x_0 \tag{1.14}$$

What constant harvest rates h can be maintained indefinitely? As Figure 1.3 shows, if h is sufficiently small, Eq. (1.14) has two equilibrium x -values, x_1 , and x_2 . The first, x_1 , is unstable, in the sense that any perturbation of x from x_1 causes $x(t)$ to diverge from x_1 . On the other hand, x_2 is a stable equilibrium in the sense that $x(t) \rightarrow x_2$ (as $t \rightarrow \infty$) in the vicinity of x_2 . Check that these assertions follow immediately from Eq. (1.14). We conclude that the constant harvest rate h is sustainable provided the following conditions are satisfied:

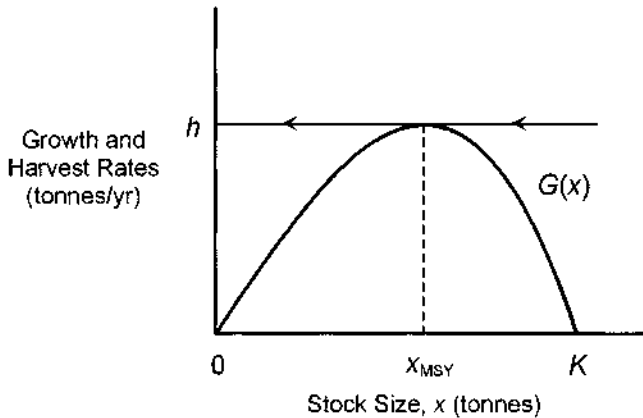


Figure 1.4 Maximum sustained yield h_{MSY} results in a semi-stable population equilibrium x_{MSY} .

1. $h < \max_x G(x)$
2. $x_0 > x_1$

On the other hand, if $h > \max G(x)$ then the population is reduced to extinction in finite time, since $dx/dt < 0$ always.

Putting these mathematical results in words, we have the following predictions from our model:

1. Sufficiently low harvest rates can be sustained in perpetuity.
2. Harvest rates that are too high will, if maintained, eventually exterminate the population.

The largest harvest rate that can be sustained indefinitely is called the *Maximum Sustained Yield*, or *MSY*. For our model this is given by

$$h_{MSY} = \max_x G(x) \quad (1.15)$$

For this value of h the two equilibria x_1 and x_2 coincide; we write x_{MSY} for the common value; see Fig. 1.4. Note that

$$G'(x_{MSY}) = 0 \quad (1.16)$$

where $G'(\cdot)$ denotes the derivative of G . MSY has long been envisioned as the ideal objective of fishery management (and of renewable resource management generally). But MSY has a number of potential shortcomings (Larkin 1977; Mangel et al. 2002), as will become clear in the sequel. Our current model already suggests one difficulty. Namely, the population equilibrium at x_{MSY} is a semi-stable equilibrium. Note that (with $h = h_{MSY}$) we have $dx/dt < 0$ for all $x \neq x_{MSY}$ – see Fig. 1.4.

This observation has important management consequences. Suppose that biologists have estimated a general production model, thereby producing an estimate of h_{MSY} . The management agency then sets its annual catch quota for the fishery according to this estimate. But what if the estimates turn out to be inaccurate? The annual harvests may exceed the true MSY for a number of years, leading to depletion of the population. Unless harvest rates are reduced, perhaps greatly reduced, the fishery may collapse. Note that the rate of population decline $h - G(x)$ increases rapidly as the stock level x is reduced below x_{MSY} . This phenomenon was clearly demonstrated in the collapse of the cod fishery in Atlantic Canada in 1991 due to overfishing – see Myers et al. (1997). Many other such examples are discussed by Dulvy et al. (2003).

Feedback harvest strategies

How should the MSY harvest strategy be modified to remove the possibility of overharvesting (Fig. 1.4)? The answer, obviously, is that the harvest rate h should be reduced whenever the stock $x(t)$ falls below x_{MSY} . A harvest strategy in which the rate of harvest depends on the current size of the resource is called a *feedback* strategy. One example for our present model would be

$$h = h(x) = \begin{cases} h_{MSY} & \text{if } x(t) \geq x_{MSY} \\ 0 & \text{if } x(t) < x_{MSY} \end{cases} \quad (1.17)$$

This somewhat extreme strategy would close the fishery completely at the first sign of overfishing. Perhaps you can think of a less extreme, but still conservationist, feedback harvest strategy.

Notice that the implementation of any feedback strategy presumes that the current stock level $x(t)$ is accurately known at all times t . The management authority continually assesses the state of the resource, and prohibits harvesting if it falls below the specified target x_{MSY} . Is this a reasonable assumption?

Perhaps not surprisingly, stock assessment for marine fish populations is a difficult undertaking, simply because the population is not directly observable. The standard method is to infer the current stock size from past catch data, but this almost invariably produces a biased estimate (Walters and Martell 2004). What this means, at least for fisheries, is that resource management usually operates under considerable uncertainty. Chapter 7 will discuss this important topic, but meanwhile we will continue to use deterministic (that is, non-random) bioeconomic models. In practice, a feedback harvest strategy will typically include some kind of safety factor to hedge against inevitable errors.

Return for a moment to Eq. (1.16):

$$G'(x_{MSY}) = 0$$

Recall that $G(x)$ represents the net natural rate of growth of the resource stock at level x . Economists would refer to $G(x)$ as the “productivity” of the resource, in which case Eq. (1.16) states that productivity is maximized when *marginal productivity*

equals zero. (The phrase “marginal X ” in economics is synonymous with “the derivative of X .”)

Note also that marginal productivity is negative for $x > x_{\text{MSY}}$ and vice versa. The management prescription “manage for MSY” could therefore be restated as “adjust the resource stock until marginal productivity equals zero.” Perhaps you can think of some reasons why this prescription may be less than eminently desirable. We will discuss some such reasons shortly.

The above discussion assumes a constant harvest rate $h(t) = h$. Time-varying harvest rates are often used, however. For example, imagine an unexploited resource stock, with $x_0 = K$. A harvest rate much larger than h_{MSY} might then be used initially, and this would not necessarily destroy the resource, provided that the rate of harvest is eventually reduced to a safe level.

One might then ask, what is the *dynamically optimal* harvest strategy? I suggest that the reader take a moment to think about this question. How could the question be precisely formulated? Imagine, for example, that you actually own such a resource stock – how would you plan the harvest?

First you need to specify an objective function to be optimized. For example, you might decide to maximize the total harvest over a certain time period $0 \leq t \leq T$. Can you see what the optimal harvest strategy is (for our present model) in this case? The answer may not be immediately obvious.

Here is how to set the problem up mathematically. If $h(t)$ is used for $0 \leq t \leq T$ then

$$\text{Total harvest} = \int_0^T h(t) dt \quad (1.18)$$

We wish to maximize this, subject to the conditions

$$\frac{dx}{dt} = G(x) - h(t) \quad x(0) = x_0 \quad (1.19)$$

$$x(t) \geq 0, \quad h(t) \geq 0 \quad \text{for all } t \quad (1.20)$$

This is a *dynamic optimization* problem – not a topic normally taught in elementary math courses! We discuss techniques of dynamic optimization in Chapter 2. The present case can be solved by elementary means, however. Giving this simple argument here is worthwhile in several ways. First, the optimal strategy agrees with frequently observed behavior in renewable resource industries; second, the solution is intuitively appealing; finally, understanding the simple case helps in understanding more complex optimization problems later on.

To solve the optimization problem, we proceed as follows:

$$\begin{aligned} \int_0^T h(t) dt &= \int_0^T (G(x) - \frac{dx}{dt}), \quad \text{by Eq. (1.19)} \\ &= \int_0^T G(x) dt + x_0 - x(T) \end{aligned} \quad (1.21)$$

The optimal harvest strategy is now almost apparent. To maximize the integral in Eq. (1.21) we need to have $x = x_{\text{MSY}}$ as given by Eq. (1.16). Thus a high initial rate of

harvest should be used to reduce x from x_0 to x_{MSY} as rapidly as possible. Indeed, since we have specified no maximum harvest rate, an infinite “pulse” harvest rate should be used at $t = 0$.

Then for $0 < t < T$ we use the MSY harvest rate h_{MSY} ; this maintains the stock at x_{MSY} . Finally at the terminal time T we perform another pulse harvest instantly reducing the population to zero. Thus the optimal harvest strategy $h^*(t)$ is given by

$$h^* = \begin{cases} x_0 - x_{MSY} & \text{at } t = 0 \text{ (pulse harvest)} \\ h_{MSY} & \text{for } 0 < t < T \\ x_{MSY} & \text{at } t = T \text{ (pulse harvest)} \end{cases} \quad (1.22)$$

The resulting total harvest is

$$\text{Total harvest} = h_{\max}T + x_0$$

In control theory (Chapter 2), the strategy of Eq. (1.22) is called a “bang-bang, singular” control.

In words, the optimal dynamic harvest strategy (for the objective of maximizing total long-term yield) is to first rapidly reduce the population to its MSY level, and then to harvest it sustainably at MSY. (The fixed terminal time T is clearly artificial – the final extermination of the resource should never actually occur in practice.)

What about the pulse harvest at $t = 0$? Is this realistic? Not entirely, because a pulse harvest implies an infinite harvest rate for an infinitesimal time instant (i.e., a Dirac “delta function”). In practice there would normally be a maximum rate at which the resource could be harvested. To include this possibility we add the constraint

$$h(t) \leq h_{\max} \quad (1.23)$$

to the conditions of Eq. (1.20). Here h_{\max} is a constant. The optimal harvest strategy now becomes

$$h^*(t) = \begin{cases} h_{\max} & \text{if } x(t) > x_{MSY} \\ h_{MSY} & \text{if } x(t) = x_{MSY} \end{cases} \quad (1.24)$$

(ignoring the terminal harvest). This is also a bang-bang singular control strategy. The resource stock is harvested at the maximum possible rate initially, until the stock has been reduced to the MSY level.

Next, what about the possibility that $x_0 < x_{MSY}$, i.e., the resource is initially in a depleted state? At time $t = 0$ harvesters agree to switch to an MSY policy. If the objective is still to maximize total future yield, then we merely add the following harvest prescription to Eq. (1.24):

$$h^*(t) = 0 \text{ if } x(t) < x_{MSY} \quad (1.25)$$

Once again this represents bang-bang control, here using the minimum harvest rate $h = 0$ until the stock has increased to the MSY level. Figure 1.5 depicts the overall optimal harvest dynamics. It should be clear that the optimal harvest strategy for these other cases is as described, by the same reasoning as before. Namely, in order to maximize the total harvest over time it is necessary, by Eq. (1.21), to maximize

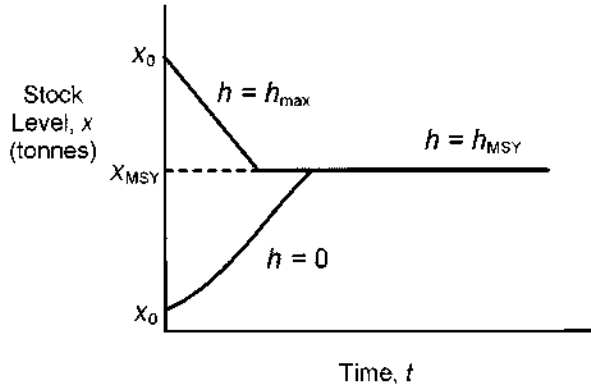


Figure 1.5 Stock dynamics $x(t)$ for the maximum total harvest strategy (infinite time horizon T). Two cases are depicted, $x_0 < x_{MSY}$ and $x_0 > x_{MSY}$.

resource production $G(x)$ by shifting the population size $x(t)$ to x_{MSY} as quickly as possible. This is accomplished by using the most-rapid approach strategy as depicted in the figure.

Something akin to most-rapid approach harvesting is often observed in newly developing resource industries. An example to be discussed later is provided by the Antarctic whaling industry in the twentieth century (Clark and Lamberson 1982). Populations of large whales in the Antarctic were rapidly reduced to low levels following the construction of floating factory vessels in the 1920s. Indeed, the production of whale oil was initially so great that oil prices plummeted, prompting the whalers to agree on annual catch quotas. However, no attempt was made to attain MSY, the reason being that the whalers were more attracted to short-term profits (which were immense) than to the prospect of sustained harvesting. We will analyze this situation in considerable detail later.

This example indicates that we now need to extend our biological model to include economic components. Before doing so, however, let us pause to criticize this, our first dynamic optimization model. The bang-bang initial harvest strategy seems a bit extreme, and the whaling example suggests why. An initial pulse harvest (or even a rapid if finite-rate initial harvest) may be unwise if this floods the market. Dealing with this possibility mathematically requires a more sophisticated use of dynamic optimization, however – see Chapter 2. Also, as already hinted, MSY itself may have undesirable aspects in practice. We postpone discussion of this point, however.

EXERCISES

1.3 Consider the (unharvested) population trajectory, i.e., solution of $dx/dt = G(x)$; see Fig. 1.2. Show that the inflection point on this curve occurs at $x = x_{MSY}$.

1.4 Calculate x_{MSY} and h_{MSY} for the logistic population model. Also show that the equilibrium states for constant rate harvesting at rate h are given by

$$x_i = \frac{K}{2} \left(1 \pm \sqrt{1 - \frac{4h}{rK}} \right)$$

What happens to this expression at the bifurcation associated with MSY?

1.5 Assuming a logistic model, scientists estimated the following parameter values for the Antarctic blue whale population: $r = .05/\text{yr}$, $K = 150,000$ whales. Calculate h_{MSY} for this population. (Actual landings of Antarctic blue whales exceeded 15,000 per annum from 1929-36, with one exception. When whaling resumed following World War II, catches exceeded 5,000 per annum from 1947-52, but then declined towards 0. The International Whaling Commission declared a moratorium on blue whales in 1965. The population of Antarctic blue whales at that time was considered to be below 5,000. See Clark and Lamberson 1982.)

Approximately how long will it take for the blue whale population to recover to x_{MSY} if the above estimates are correct?

1.6 For some species a discrete-time model of population dynamics is appropriate, for example

$$X_{t+1} = F(X_t - H_t), \quad t = 1, 2, 3, \dots$$

where X_t now denotes the population size prior to the annual fishing season (t representing the year index), and H_t is the year's harvest. The difference $S_t = X_t - H_t$ is called the *escapement*. (This model applies only to species with non-overlapping generations.) If F is known, what equation determines the escapement level S for maximum sustained yield?

1.4 A BIOECONOMIC MODEL

It may seem that maximizing the total (and hence sustained) yield from a given renewable resource stock is necessarily economically optimal. Why would one want anything less than the maximum yield? This "obviously optimal" concept has dominated resource management for many decades. It always seems to take resource scientists by surprise when fishermen (for example) object strenuously to MSY-based regulations, as they invariably do. (Corson 2005 wittily describes the never-ending controversies between fishermen and scientists in the Maine lobster fishery, for example.) Any viable theory of resource economics must satisfactorily explain this phenomenon.

In fact there are two explanations, depending to some extent on the socio-economic circumstances under which the resource is harvested. The bioeconomic model used in this section will incorporate both explanations, explaining how they interact. As will be apparent, a fully dynamic (time-dependent) model is essential for this study. Some economic textbooks cover the topic using a static model, *but this is hopelessly misleading*. It's a perfect example of failing to recognize the assumptions

and limitations of a partly successful model. Among other things, a static model of resource economics by-passes the whole question of conservation, which as we have seen is fundamentally dynamic. Likewise, a static model ignores the natural-capital aspect of resource economics.

We continue to use our basic biological model

$$\frac{dx}{dt} = G(x) - h(t), \quad x(0) = x_0 \quad (1.26)$$

$$x(t) \geq 0, \quad h(t) \geq 0 \quad (1.27)$$

We also introduce a new variable, $E(t)$ = harvesting *effort* at time t . In the fisheries setting, $E(t)$ is typically specified as the number of (standard) vessels actively fishing at time t . Units of effort would then be Standard Vessel Units (SVU).

We will adopt the commonly used *catch-effort relation*

$$h = qEx \quad (1.28)$$

where q is a constant, called *catchability*. Units of q are $\text{SVU}^{-1} \times (\text{time unit})^{-1}$. Thus q represents the proportion of the current stock x caught by one standard vessel in one time unit. To be specific we will now use time units of days (rather than years). Thus $G(x)$ now represents population growth per day and $h(t)$ is the daily harvest rate, both being measured in tonnes per day.

Equation (1.28) is often called the Schaefer catch-effort relation, after fisheries biologist M.B. Schaefer (1954). The ideas behind this assumed catch relation are, first that catch rates should be higher if the fish population is larger, and second that the total catch rate should increase in proportion to fleet size. The Schaefer equation $h = qEx$ specifically models these dependencies as linear proportionalities forming a combined bilinear function. Some important limitations of the Schaefer model will be discussed later.

We introduce economic parameters:

$$p = \text{ex-vessel price of fish (\$/tonne)}$$

$$c = \text{cost of effort (\$/SVU day)}$$

Daily net revenue for the fishery as a whole is given by

$$\text{Daily revenue} = R = ph - cE$$

or by Eq. (1.28)

$$R = (pqx - c)E \quad (1.29)$$

(in \$/day). Note also that daily net revenue per standard vessel is just $pqx - c$. The value R , i.e., total net daily revenue from the fishery, is called the (daily) *economic rent* obtained from the resource.

An important prediction from this model is that fishing is profitable if and only if

$$x > \frac{c}{pq} \quad (1.30)$$

Write

$$x_{BE} = \frac{c}{pq} \quad (1.31)$$

(the subscript BE signifies Bionomic Equilibrium – see below). Then fishing is profitable at stock level x if and only if $x > x_{BE}$.

Bionomic equilibrium

We now investigate the case of a completely unregulated, open-access fishery – a situation that still prevails in many high-seas fisheries. If $x(t) > x_{BE}$ fishing is profitable, so we expect that fishing will take place, i.e., $E(t) > 0$. We cannot predict from our present model how large $E(t)$ will be, but let us suppose that E will tend to be very large whenever fishing is profitable. If so, fishing will rapidly reduce the stock level down to x_{BE} .

Now, what will happen next? As soon as $x(t)$ falls below x_{BE} fishing ceases. However, natural population growth continues, so $x(t)$ increases once fishing pressure is removed. When $x(t)$ rises above x_{BE} fishing resumes, and so on. Thus we expect that a somewhat tenuous equilibrium will become established at or around the stock level x_{BE} . The stock level x_{BE} is called the *bionomic equilibrium* of the unregulated open-access fishery. Note that from Eq. (1.29) we have $R = 0$ at bionomic equilibrium.

The main prediction of this discussion is that (Gordon 1954)

Unregulated fishing (by competing fishermen) will drive the resource stock to bionomic equilibrium, at which economic rents are reduced to zero.

This is a leading principle of resource economics. It applies to many examples other than fisheries. Indeed, any biological resource stock that is exploited under uncontrolled competition will ultimately be reduced to bionomic equilibrium. Examples include wildlife, forests, grazing lands, and so on. The term “tragedy of the commons” (Hardin 1968) is also used to describe this phenomenon.

Three questions immediately arise. First, does bionomic equilibrium often occur in practice? Second, is bionomic equilibrium necessarily a bad thing, and how bad can it get? Third, what can be done to prevent bionomic equilibrium from occurring? Let us foreshadow the ensuing discussions by stating that:

1. Bionomic equilibrium in resource exploitation has occurred throughout history, and is still extremely common today.
2. Bionomic equilibrium can be, and often is, economically devastating; it can also result in a severely depleted resource stock. Indeed, complete extermination of the stock is a possibility.
3. Preventing bionomic equilibrium has often turned out to be far more difficult than anticipated.

The term bionomic equilibrium is unfortunately somewhat inaccurate. Since x_{BE} is determined by economic parameters p , c , q , bionomic equilibrium will change over

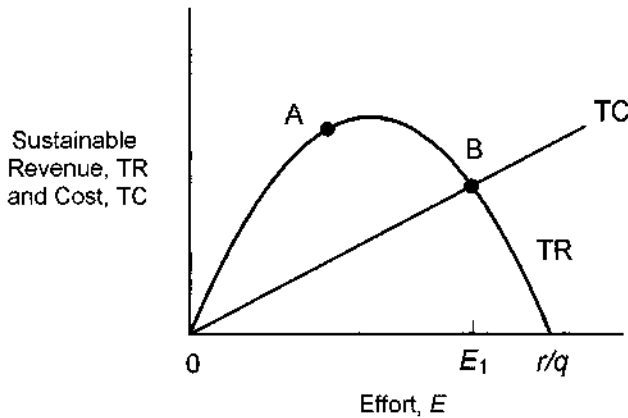


Figure 1.6 Sustainable total revenue TR and cost TC of harvesting a biological population. Bionomic equilibrium occurs at $E = E_1$, where revenue equals cost; this is point B . (Note: this diagram can be highly misleading because of its neglect of resource dynamics.)

time as these parameters change. For example, human population growth may result in increasing demand for resources, meaning that resource prices tend to increase over time. Also, technological advances can lead to lower cost c or higher harvest efficiency q , or both. All these changes cause x_{BE} to decrease over time.

In the case of marine fisheries, for example, depletion of fish stocks has gradually extended from readily accessible near-shore to remote offshore populations. Large-sized, valuable species have been progressively overfished or eliminated (Myers and Worm 2003), in a process that Pauly has called “fishing down the food web” (Pauly et al. 1998).

Similarly, deforestation has progressed historically from early to modern civilizations, and today threatens to destroy many of the great remaining tropical and temperate rain forests. Diamond (2005) attributes the collapse of past civilizations largely to their destruction of renewable resources.

Figure 1.6 is a standard textbook representation of the concept of bionomic equilibrium. The horizontal axis represents harvesting effort E , while the vertical axis represents sustainable revenue and costs. Note carefully the adjective “sustainable;” this diagram is often presented without stressing this proviso. The resulting analysis in this case can be devastatingly incorrect, at least in part, as will shortly be explained.

At the level of abstraction incorporated in Fig. 1.6, harvesting effort is simply an index of total economic inputs to the harvesting process. The number of active fishing vessels, or the number of active deer hunters, would be specific examples. Effort cost C is assumed, not unreasonably, to be proportional to effort. More importantly, the revenue curve R is assumed to rise to a peak, and then to decline, as effort is increased. This feature, which goes beyond the usual assumption of “decreasing returns to scale” as encountered in economics texts, is a specific consequence of the basic properties of a biological resource population. To be precise, high levels

of harvesting effort can result in the depletion of the population to a level at which net biological reproduction is reduced, ultimately approaching the extinction of the population. When a certain fish population is reduced to, say 10% of its unfished biomass, because of high inputs of effort, sustained catches can become greatly reduced – as has indeed often been the case.

Figure 1.6 leads to the same prediction of bionomic equilibrium that we have been discussing. Namely, if the input of harvesting effort is unregulated, and effort is contributed by many competing harvesters, then an equilibrium will become established at $E = E_1$, the point at which sustained total revenue R equals the cost of harvesting C . To repeat the argument for this diagram, at any level of effort $E < E_1$ we have $R > C$, so harvesters are enjoying positive net benefits. Consequently, additional harvesters will be attracted to the resource in question. On the other hand, if $E > E_1$ then net revenues have become negative, and harvesters will tend to leave the resource. A sustained equilibrium results only when $E = E_1$, and this is the bionomic equilibrium.

Thus Figure 1.6 leads to the same conclusion that we reached before, but without explicit reference to the population stock $x(t)$. Indeed, the current argument was the one originally given by Gordon (1954), in his analysis of the so-called common-property fishery. As far as the prediction of bionomic equilibrium is concerned, the Gordon diagrammatic model is entirely correct.

In what way is Fig. 1.6 misleading, then? The paper of Gordon itself shows how. Gordon asserted that optimal fishing would maximize the difference $R - C$, between revenue and cost. This requires that marginal revenue equals marginal cost:

$$\frac{\partial R}{\partial E} = c$$

As can be seen from Fig. 1.6 (point A), this condition determines an effort level $E = E^*$ that lies to the left of the peak on the revenue curve. Therefore, under optimal fishing, the fishermen will be harvesting less than the maximum sustainable yield. Fishermen should be strict conservationists. They should vehemently support management programs that limit fishing effort to the optimal level E^* , because this will both increase their incomes and decrease their costs.

For example, suppose that each fisherman involved in bionomic equilibrium reduces his effort by 50%, by fishing half-days. His costs will instantly decline by 50% and his net revenue will increase from zero to some positive level. Geronimo!

Can you see anything suspicious about this prediction? Could there be any reason why the fishermen might see the situation differently? If you don't see this immediately, *you're not alone*.

The fishermen do usually see it immediately, so try to think like a fisherman (not like an academic). Let's say you're now catching 1 tonne of fish per week by fishing 12 hours a day for 7 days. Suddenly you agree to fish 6 hours a day (as does everyone else). What will happen? Obviously you will now catch 0.5 tonnes per week. Your revenues will decrease by 50%, and so will your costs. So you're exactly where you started, with zero net income for the week.

So what's wrong with Fig. 1.6? What happened to the predicted emergence of positive net income $R - C$? Look at the diagram again, and read the legend again.

Got it? The catch is the word "sustainable." Figure 1.6 is a graph of sustainable revenue (and sustainable cost). It is not a graph of the immediate, short-term response of revenue R to effort E . In the short term, one's daily catch of fish will be more or less proportional to one's daily effort E (depending on how lucky one is that day). If every fisherman reduces his effort by 50%, the total day's catch will also decline by 50% approximately.

What Fig. 1.6 depicts is the long-term response of the fish population to different levels of effort. If effort E is reduced permanently by 50% from E_1 , the fish population will begin to recover from overfishing. Eventually it will reach a new, larger equilibrium population level, and R will therefore become larger, as predicted. The only question is, how long will it take to reach the new equilibrium? Weeks? Years? Decades? Most fish populations take years or decades to recover from severe overfishing. Some may never recover (but we ignore that possibility for now). Figure 1.6 simply ignores the time dimension, yet fishermen and other resource harvesters have to feed their families today.

Clearly we need to include resource dynamics in our bioeconomic theory. Again, resource conservation is a dynamic problem, one that cannot be adequately addressed with static models such as that depicted in Fig. 1.6.

Does the above discussion imply that harvesters will always be opposed to resource conservation? Certainly not. But it is true that successful resource management must fully take account of the time dimension. This is the main theme of *Mathematical Bioeconomics*.

The extent to which bionomic equilibrium implies resource depletion depends on how small $x_{BE} = c/pq$ is, relative to x_{MSY} . In the case that $x_{BE} > x_{MSY}$ we would say that the stock is not currently overfished, and vice versa.

There is no limit as to how low x_{BE} may be. Our biological model, with $G(x)$ satisfying Eqs. (1.4)-(1.6), predicts that the population will persist indefinitely at any level x_{BE} no matter how low. Also, the population will always recover if fishing ceases. In actuality, many fish populations have failed to recover from severe overfishing (Hutchings 2000). Many other renewable resource populations have also been exterminated by overharvesting. For example, many of today's deserts were formerly productive farms or grazing lands (Alsharhan 2003). The reasons why a given depleted population fails to recover after harvesting ceases are seldom fully understood. Two possibilities are, first that reproductive success may fall below sustainability levels when the stock is sufficiently low, and second that a depleted population may be replaced by a competing species. These effects can be included in our model if the growth function $G(x)$ is modified so that

$$G(x) < 0 \quad \text{for } x < x_{MVP}$$

where x_{MVP} denotes a minimum viable population; see Fig. 1.7. Such a growth function is said to exhibit *critical depensation* (Liermann and Hilborn 2001). If $x_{BE} < x_{MVP}$ the population will become extinct under unregulated exploitation.

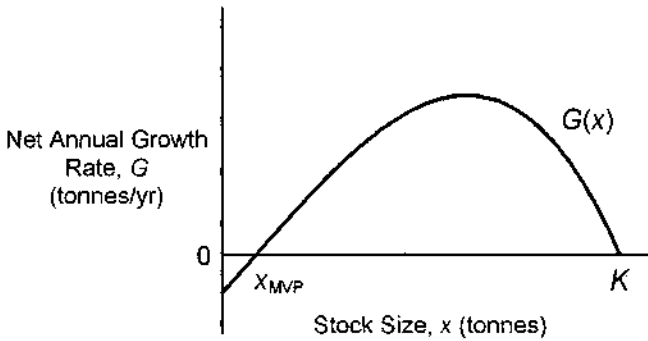


Figure 1.7 Natural growth function with critical depensation; if x falls below x_{MVP} the population crashes to zero.

The idea of depensation in population dynamics is mathematically appealing, perhaps, but in practice one would never know if a given population would be subject to depensation until the “experiment” of overharvesting had been tried. This and other sources of uncertainty in resource management will be discussed in Sec. 1.8.

Next, how bad is bionomic equilibrium, in economic terms? Recall that, once bionomic equilibrium is reached, economic rents (revenues minus costs) become zero. Higher biomass levels than x_{BE} provide positive sustainable rents. We spend the rest of this section discussing this important point. Historically, the analysis of this question was for some time seriously mis-handled, because of a failure to consider the dynamic implications of resource harvesting. We start by looking briefly at the equations of the static model, and then go on to explain why the static model is misleading. The dynamic optimization problem, once formulated, is then solved by a natural extension of the method used to solve the similar case of Eqs. (1.18)-(1.20).

Maximum sustained economic yield

To calculate the sustainable economic yield (rent) at a given biomass level x , we set $h = qEx$ in Eq. (1.26) and then apply the steady-state condition $dx/dt = 0$:

$$G(x) = qEx$$

The sustained rent R_{SUST} is then given by

$$R_{SUST} = (pqx - c)E = (pqx - c)G(x)/qx$$

or

$$R_{SUST} = \left(p - \frac{c}{qx}\right)G(x)$$

(see Fig. 1.8). Writing

$$c(x) = \frac{c}{qx} \tag{1.32}$$

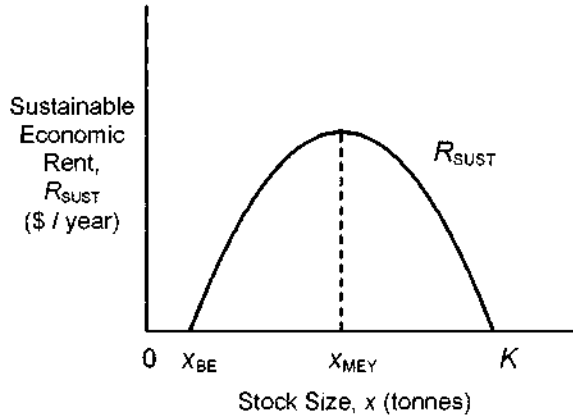


Figure 1.8 Sustainable economic rent R_{SUST} as a function of steady-state biomass level x ; see Eq. (1.33).

we have

$$R_{SUST} = (p - c(x))G(x) \quad (1.33)$$

We have $R_{SUST} > 0$ for $x_{BE} < x < K$, and $R_{SUST} = 0$ at both ends of this interval (Fig. 1.8). Hence R_{SUST} reaches a maximum at some interior value $x = x_{MEY}$ (the subscript MEY, which is traditional in fisheries economics, designates Maximum Economic Yield). By differentiation of Eq. (1.33) we obtain

$$G'(x) - \frac{c'(x)G(x)}{p - c(x)} = 0 \quad \text{for } x = x_{MEY} \quad (1.34)$$

The function $c(x)$ in Eq. (1.32) represents the cost of a unit harvest (e.g., one tonne) when the stock level is x . (To see this, write $h = qEx = 1$, so that cost $= cE = c/qx$.) Note that the unit harvest cost is inversely proportional to stock size x . For our (Schaefer) fishery model, unit harvesting costs increase in inverse proportion as the stock level x is fished down. Bionomic equilibrium is reached when the cost of catching an additional unit of fish is equal to the value of that unit, i.e., when $c(x) = p$. This is the same as Eq. (1.31).

Let us now examine Eq. (1.34), which determines x_{MEY} , the biomass level for maximum sustainable economic yield (rent). This is our first genuine bioeconomic result, involving both the biological growth function $G(x)$ and the economic parameters of price and cost. Note, to begin with, that Eq. (1.34) is an extension of the marginality equation for x_{MSY} – see Eq. (1.16). In particular, Eq. (1.34) reduces to Eq. (1.16) if fishing costs are zero; in this case $x_{MEY} = x_{MSY}$. If fishing costs are nonzero, we conclude from Eq. (1.34) that

$$x_{MEY} > x_{MSY} \quad (\text{if } c \neq 0) \quad (1.35)$$

(This tacitly assumes that $G'(x)$ is decreasing, i.e., that $G''(x) < 0$, which we henceforth do assume.)

The term $-c'(x)G(x)/(p - c(x))$ in Eq. (1.34) is called the *marginal stock effect* (Clark and Munro 1975). This expression is positive for $x_{BE} < x < K$, because $c'(x) < 0$. Thus

$$G'(x_{MEY}) = \frac{c'(x_{MEY})G(x_{MEY})}{p - c(x_{MEY})} < 0$$

and this proves Eq. (1.35). In words, since the unit harvest cost $c(x)$ is decreasing in x , it is desirable to maintain a higher stock level than would otherwise be the case.

Gentle reader, I have to admit that I have been leading you down the garden path, so to speak. You may think that I am proposing maximum economic yield x_{MEY} as an economically optimal management objective, and indeed that was exactly what at one time was proposed by many fisheries economists. But this prescription ignores a fundamental aspect of resource economics. Re-read Section 1.1 to remind you of what this aspect is. We will re-introduce this aspect shortly.

EXERCISES

1.7 Show that for the logistic growth model of Eq. (1.12) we have $x_{MEY} = x_{MSY} + \frac{1}{2}x_{BE}$. Suggestion: first show that R_{SUST} of Eq. (1.33) can be written in the form $R_{SUST} = a(x - b)(c - x)$ for certain constants a, b, c .

1.8 This exercise derives the original model of H. Gordon (1954) for bionomic equilibrium in an open-access fishery. Assume a logistic growth function $G(x) = rx(1 - x/K)$ and a Schaefer catch equation $h = qEx$.

- For any fixed effort level E let $Y(E)$ denote the sustainable yield (i.e., harvest rate) corresponding to E . Find the equation for $Y(E)$.
- Sketch the total revenue curve $TR = pY(E)$ and total cost curve $TC = cE$ on the same graph. Identify the points of bionomic equilibrium and maximum economic yield on this graph. This graph is how Gordon (1954) formulated his theory of the common-property (open-access) fishery. Note that the role of the biological resource stock x is entirely suppressed in this theory. Gordon's theory is sometimes described as the *static model* of fishery bioeconomics, because of the fact that the yield curve $Y(E)$ consists of static, or equilibrium, solutions to the dynamic model.

1.9 Show that the Gordon model of Exercise 1.8 leads to the following predictions.

- There is a cost-price threshold such that the fishery is not economically viable if the cost-price ratio c/p is above the threshold. How is the threshold related to Eq. (1.31) for x_{BE} ?
- Bionomic equilibrium never results in the extinction of the fish population. (As we explain later, this prediction is model specific; it is not valid under alternate model assumptions.)
- MEY is always "more conservative" than MSY.

1.5 A DYNAMIC OPTIMIZATION MODEL

We again list our basic dynamic model:

$$\frac{dx}{dt} = G(x) - h(t), \quad x(0) = x_0 \quad (1.36)$$

$$h(t) = qE(t)x(t) \quad (1.37)$$

$$R(t) = ph(t) - cE(t) = (p - c(x(t)))h(t) \quad (1.38)$$

$$c(x) = \frac{c}{qx} \quad (1.39)$$

$$x(t) \geq 0, \quad E(t) \geq 0 \quad (1.40)$$

As mentioned in Sec. 1.1, the usual objective used in investment analysis and in cost-benefit analysis is the *discounted present value* of future net revenues. This can be expressed as

$$PV = \int_0^{\infty} e^{-\delta t} R(t) dt \quad (1.41)$$

where δ denotes the instantaneous *discount rate*.

Discounting is the time-reverse of compound interest. Consider an amount V_0 invested today at continuous compound interest rate δ . Then by definition, the value of the investment will increase according to $dV/dt = \delta V$. Hence

$$V(t) = V_0 e^{\delta t}$$

Inverting this, we obtain

$$V_0 = e^{-\delta t} V(t)$$

which says that the present value V_0 of a (single) future payment $V(t)$ at time t is calculated by discounting $V(t)$ by the factor $e^{-\delta t}$. For example, what you pay today for a treasury bill, or a bond, that matures after time t , is calculated from this present-value formula.

The integral in Eq. (1.41) therefore equals the total present value of a stream of time-payments $V(t)$, $t \geq 0$, using the constant discount rate δ .

We now face a well-defined dynamic optimization problem:

$$\text{maximize}_{\{E(t)\}} PV \quad (1.42)$$

subject to Eqs. (1.36)-(1.40).

That is, we wish to determine the effort strategy $E(t)$, $t \geq 0$ that results in the largest possible net economic benefit as expressed by the present value integral PV of Eq. (1.41). Such dynamic optimization problems are the essence of the theory of capital and investment.

How does one solve a dynamic optimization problem? This task is greatly facilitated by a mid-twentieth century technique called optimal control theory, which we will discuss in Chapter 2. Here we will use instead a direct method that is an

extension of the method used earlier in this chapter for maximizing the total harvest $\int_0^T h(t)dt$ – see Eqs. (1.18)-(1.20).

(A certain special feature of our present optimization problem allows us to use the direct method. Make any substantial change to the model and you lose this opportunity. More on this in Ch. 2.)

We wish to maximize, by choice of the future harvest strategy $h(t) = qE(t)x(t)$, the integral

$$PV = \int_0^{\infty} e^{-\delta t} (p - c(x))h(t)dt$$

given that

$$\frac{dx}{dt} = G(x) - h(t), \quad h(t) \geq 0$$

First, we substitute for $h(t)$ in the PV integral:

$$PV = \int_0^{\infty} e^{-\delta t} (p - c(x)) \left(G(x) - \frac{dx}{dt} \right) dt$$

Next, we introduce a new variable

$$z(x) = \int_{x_{BE}}^x (p - c(u))du \quad (1.43)$$

($z(x)$ has an economic interpretation, which we discuss later.) We have

$$\frac{dz}{dt} = \frac{dz}{dx} \frac{dx}{dt} = (p - c(x)) \frac{dx}{dt}$$

Our PV interval now becomes

$$PV = \int_0^{\infty} e^{-\delta t} \left[(p - c(x))G(x) - \frac{dz}{dt} \right] dt$$

By integration by parts we have

$$\begin{aligned} \int_0^{\infty} e^{-\delta t} \frac{dz}{dt} dt &= [e^{-\delta t} z(x(t))]_0^{\infty} + \delta \int_0^{\infty} e^{-\delta t} z dt \\ &= \delta \int_0^{\infty} e^{-\delta t} z dt - z(x(0)) \end{aligned}$$

so that now

$$PV = \int_0^{\infty} e^{-\delta t} [(p - c(x))G(x) - \delta z] dt + z(x_0) \quad (1.44)$$

From this expression, the nature of the optimal harvest strategy becomes evident. Namely, the expression in the square brackets should be maximized for all t , or at least as rapidly as possible.

Let x^* maximize the expression

$$(p - c(x))G(x) - \delta z$$

By differentiation we have, from Eq. (1.43)

$$(p - c(x^*))G'(x^*) - c'(x^*)G(x^*) = \delta z'(x^*) = \delta(p - c(x^*))$$

which can be written as

$$G'(x^*) - \frac{c'(x^*)G(x^*)}{p - c(x^*)} = \delta \quad (1.45)$$

Equation (1.45) is the main bioeconomic result of this chapter. It specifies an economically "optimal" equilibrium biomass level x^* . Optimal is in quotation marks here to emphasize that this result depends on several assumptions, any of which may not be valid in practice. We can assert, however, that the private owner of a renewable resource stock would wish to operate at the stock level x^* , provided these assumptions did apply to his situation.

We need to address the following questions:

1. What is the optimal way to shift the stock from its initial level x_0 to the long-term equilibrium x^* ?
2. How does x^* depend on the model parameters?

Later on we will also ask:

3. Which model assumptions are most important, and what happens if these assumptions are changed?

In addition, we need to pay careful attention to the following question:

4. Assuming that optimal biomass level differs strongly from bionomic equilibrium, how can the resource be managed so as to obtain optimal, or nearly optimal, results? This question is more difficult and complex than it may appear. Section 1.7 attempts to address it.

The optimal approach path

Return now to Eq. (1.44) for PV . We said that the integrated expression,

$$(p - c(x))G(x) - \delta z \quad (1.46)$$

has to be maximized over x . Also, the stock $x(t)$ should be shifted as rapidly as possible from its initial level x_0 to the desired optimum, denoted by x^* . Why? Simply because if the given expression is below its maximum value (i.e., if $x \neq x^*$) over some time interval, then the PV integral is less than it could be.

The optimal harvest strategy is therefore given by

$$h(t) = \begin{cases} h_{\max} & \text{if } x(t) > x^* \\ G(x^*) & \text{if } x(t) = x^* \\ 0 & \text{if } x(t) < x^* \end{cases} \quad (1.47)$$

where h_{\max} denotes the maximum possible rate of harvest, i.e., $h(t) \leq h_{\max}$. This strategy is known as a *bang-bang* control strategy, or as the *most rapid approach* harvest strategy. (Recall that we encountered this bang-bang strategy earlier – see Eqs. (1.24) and (1.25). If $h_{\max} = +\infty$ we get a pulse harvest, from x_0 to x^* , at $t = 0$.) Figure 1.5 shows this graphically for the earlier case; the present case is the same, except that the target stock level is now x^* rather than x_{MSY} .

By the way, rather than h_{\max} , suppose we assume a maximum effort capacity E_{\max} . Then Eq. (1.47) becomes

$$E(t) = \begin{cases} E_{\max} & \text{if } x(t) > x^* \\ E^* = G(x^*)/qx^* & \text{if } x(t) = x^* \\ 0 & \text{if } x(t) < x^* \end{cases} \quad (1.48)$$

(Another aside: the foregoing argument tacitly assumes that the function $(p - c(x))G(x) - \delta z(x)$ is convex. This is true for the logistic-Schaefer model, but not necessarily in other cases, including depensatory growth. In this case, Eq. (1.45) may yield only a locally optimal equilibrium; see Clark 1972).

The optimal stock equilibrium

What is the economic interpretation of Eq. (1.45)? Note first that this equation contains MSY, Eq. (1.16) and MEY, Eq. (1.34) as special cases. MSY is optimal under zero costs and zero discounting. MEY is optimal under zero discounting. The latter makes intuitive sense – with zero future discounting the optimal harvest strategy would maximize long-term economic benefits (rent), which is MEY. We also conclude from Eq. (1.45) that the optimal stock level x^* satisfies

$$x^* < x_{\text{MEY}} \quad \text{if } \delta > 0 \quad (1.49)$$

and also

$$x^* \text{ is a decreasing function of } \delta \quad (1.50)$$

Higher discount rates imply lower levels of conservation. In fact we have

$$\lim_{\delta \rightarrow \infty} x^* = x_{\text{BE}} \quad (1.51)$$

(see Fig. 1.9 below for graphic representation of x^*). The easiest way to see this is to recall that x^* maximizes $(p - c(x))G(x) - \delta z(x)$ where $z(x)$ is given by Eq. (1.43). If δ is very large, this amounts to minimizing $z(x)$, which implies that $x = x_{\text{BE}}$. The fact that infinite discounting leads to the same outcome as bionomic equilibrium, first argued by Scott (1955), also makes good intuitive sense. Under high discounting, future revenues count for very little, so present revenues are maximized, and this implies rapid harvesting down to x_{BE} . Or looking at it the other way around, under open-access competition, resource users must completely discount the future because they cannot expect to receive positive returns in the long run.

Table 1.1 treats an example based on the twentieth century history of Antarctic

Table 1.1 Optimal equilibrium population x^* of Antarctic blue whales as a function of the discount rate (Clark and Lamberson 1982).

Discount Rate, δ (/year)	Optimal Population, x^* (whales)	Cash-in Value, z ($\$ \times 10^6$)	Sustainable Rent, R_{SUST} ($\$ \times 10^6$ /year)
0	76,000	467.1	12.8
1%	61,488	368.5	12.3
3%	33,673	218.9	8.6
5%	12,758	49.4	3.4
10%	3,853	3.8	0.6
20%	2,647	0.6	0.2
∞	2,000	0	0

blue whale fishing. Estimated parameter values are

$$\begin{aligned}
 r &= .05/\text{year} \\
 K &= 150,000 \text{ whales} \\
 x_{BE} &= c/pq = 2,000 \text{ whales} \\
 p &= \$7,000 \text{ per whale}
 \end{aligned}$$

Note that the optimal equilibrium stock x^* is highly sensitive to the discount rate. Indeed, for $\delta > 10\%$ per annum, the optimal population differs little from $x_{BE} = 2,000$ whales. This result can be understood by examining the third and fourth columns in the table. For example, consider the case of x_{MEY} , i.e., $\delta = 0$. Sustainable rent at this stock level is \$12.8 million/year, compared to a cash-in value of \$467.1 million. The cash-in value is what the whalers would get by harvesting the blue whale population right down to x_{BE} in a single year, if that were possible. (In fact, the cash-in value at stock level x is just $z(x)$ as given by Eq. (1.43); see below.)

Which of these two alternatives, MEY or cash-in, would the whalers prefer? Note that $R_{SUST}/z = 2.74\%$ per annum, which means that by operating at MEY the whalers would be earning 2.74% annual interest on the whale "asset." It would not be surprising if the whaling industry deliberately decided to cash in their asset, under these conditions. Apparently, this decision was both conscious and deliberate, at least for the Japanese whalers (P. Ehrlich, personal communication). The whalers were certainly aware that the Antarctic whale stocks were being decimated. Catch rates of blue whales, which were as high as seven whales per catcher-day in the 1930s, had declined to around one whale every seven days by mid-century, yet the whaling continued (D. Chapman, personal communication). Similar if less severe declines were experienced for fin and sei whales in the Antarctic Ocean.

So were the whalers just greedy, or more greedy than other resource exploiters? Not necessarily. Although representatives of the whaling nations met (and still meet) annually through the International Whaling Commission to set annual quotas, mutual

trust must have been a bit shaky. The possibility of new entry to the whale fishery was always present, and this would have been more likely if whale stocks had been strongly protected. Ultimately in 1978 the IWC members agreed to cease operation in the Antarctic, although this decision could be reversed at any time.

The whaling example is used here as a clear indication that discounting can have a strong effect on renewable resource harvesting, and this remains true even when the resource is privately owned. What is it about whale biology and whaling economics that leads to extreme sensitivity of the optimal stock level x^* to the discount rate? As will become apparent shortly, any biological resource having the following characteristics will exhibit similar sensitivity to discounting:

- low biological growth rate
- long-lived individuals
- valuable resource product
- reasonably low cost of harvest

Examples of such resources include marine mammals generally, certain species of fish, sharks, trees, soils, desert plants, and so on. Such resources are characterized biologically by low growth rates, either in terms of low fecundity or slow growth of individuals. The large whales have both of the latter features.

The numerical results in Table 1.1 were calculated using the following explicit equation for x^* , which pertains to the logistic growth model $G(x) = rx(1 - x/K)$:

$$x^* = \frac{K}{4} \left[\left(\frac{c}{pqK} + 1 - \frac{\delta}{r} \right) + \sqrt{\left(\frac{c}{pqK} + 1 - \frac{\delta}{r} \right)^2 + \frac{8c\delta}{pqKr}} \right] \quad (1.52)$$

This shows that x^* depends on two particular dimensionless combinations of model parameters, namely

$$\gamma = \frac{\delta}{r} \quad (1.53)$$

and

$$y_{BE} = \frac{x_{BE}}{K} = \frac{c}{pqK} \quad (1.54)$$

If we also define $y^* = x^*/K$, then Eq. 1.51 becomes

$$y^* = \frac{1}{4} \left[(y_{BE} + 1 - \gamma) + \sqrt{(y_{BE} + 1 - \gamma)^2 + 8y_{BE}\gamma} \right] \quad (1.55)$$

in which all symbols are dimensionless. It can be shown directly that

$$y_{BE} \leq y^* \leq y_{MEY} \quad \text{and} \quad \lim_{\delta \rightarrow \infty} y^* = y_{BE}$$

where $y_{MEY} = \frac{1}{2}(y_{BE} + 1)$. This agrees with Eqs. (1.49) and (1.51).

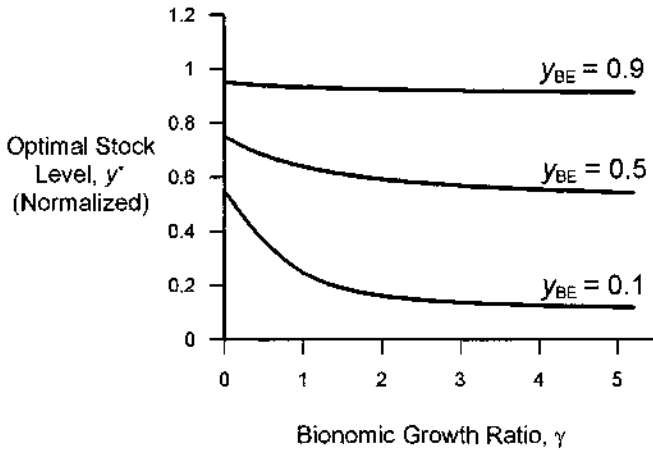


Figure 1.9 Optimal stock level y^* as a function of the bionomic growth rate γ .

We call γ the *bionomic growth ratio*. Thus the discount rate δ affects the optimal stock size via its ratio to the intrinsic growth rate of the resource. Figure 1.9 depicts the dependence of the optimal stock size y^* on the two parameters γ and y_{BE} . Note that the curves shown here are decreasing in γ , with asymptotic limit y_{BE} as $\gamma \rightarrow \infty$.

(Growth functions other than the logistic would generate different but similar curves for y^* .)

The Golden Rule

Returning to Eq. (1.45),

$$G'(x^*) - \frac{c'(x^*)G(x^*)}{p - c(x^*)} = \delta$$

let us briefly consider the case of zero harvest cost $c(x) = 0$. We then have

$$G'(x^*) = \delta \quad (1.56)$$

Expressed in words, marginal productivity of the resource asset is equal to the discount rate, when the resource stock is at its optimal level x^* (harvesting costs being zero). In the theory of optimal investment, and in optimal growth theory, Eq. (1.56) is sometimes called the *Golden Rule* of capital investment. It says that the stock of capital should be increased (or if necessary, decreased) until marginal productivity equals the rate of discount, i.e., the rate of interest. High interest rates imply low levels of investment, and vice versa. (We discuss this topic further in Chapter 3.)

Our general bioeconomic rule, Eq. (1.45), could thus be referred to as a modified Golden Rule, with the modification (the marginal stock effect) reflecting the fact that

unit harvest costs are a decreasing function of stock size x . As with the case of the Golden Rule, the optimal “investment” strategy is to adjust the size of the resource stock, either through rapid harvesting, $h = h_{\max}$, or stock rebuilding, $h = 0$, until the optimum is reached.

In optimal growth theory, x represents the size of a nation’s capital stock, and harvesting is replaced by consumption. Positive investment requires low levels of consumption, specifically $c < G(x)$, but this facilitates higher future consumption. The difference, $G(x) - c$, is net investment in the sense that

$$\frac{dx}{dt} = G(x) - c$$

An economy can only grow if its citizens consume at a rate less than the total annual production $G(x)$. An optimal capital stock x^* is reached when $G'(x^*) = \delta$. [This applies to a nation having zero population growth; otherwise a correction is needed to account for population growth.] Of course, a similar decision – balancing current consumption against saving to increase one’s wealth – faces all individual consumers. How people make their personal savings decisions is far from obvious. Credit card accounts typically charge around 18% annual interest on unpaid balances. On the other hand, current mortgage rates are below 5% per annum, while bond interest rates hover around 5% per annum. We discuss such matters more fully in Chapter 3.

By the way, the bang-bang investment strategy may seem extreme, for the growth-theory model. Should (or could) a nation undergo zero consumption while building its economy? Of course not. Economists get around this difficulty by introducing a nonlinear utility of consumption $U(c)$. The growth objective is then to maximize $\int_0^\infty e^{-\delta t} U(c) dt$ subject to $dx/dt = G(x) - c$. This has an optimal equilibrium level of capital x^* given by the Golden Rule $G'(x^*) = \delta$, with an optimal approach strategy $c(t)$ that is not bang-bang. Optimal consumption is always positive, but sufficiently small to facilitate economic growth.

We will discuss nonlinear resource revenue functions $R(x, h)$ in Chapter 2, thereby escaping from the limitations of bang-bang harvest strategies. This has great practical importance.

I hope the foregoing discussion has convinced you that resource economics is inherently a dynamic subject, the study of which demands considerable mathematical sophistication. These are not merely academic issues – on the contrary they are of fundamental importance to society. We need to develop and analyze such bioeconomic models, while maintaining a healthy attitude of scepticism. Our models can tell us lot about the world, but they are forever inadequate. For example, in the middle of writing this chapter I was suddenly confronted with a real-world fishery problem for which there was no known model. I think I made some progress, but more research will be needed, as they say!

Extinction

For the Schaefer model we deduced a unit harvest-cost function

$$c(x) = \frac{c}{qx}$$

Bionomic equilibrium x_{BE} occurs when $p = c(x)$, i.e.,

$$x_{BE} = \frac{c}{pq}$$

Harvesting ceases whenever $x < x_{BE}$. Thus unless $c = 0$ our model predicts that commercial harvesting will not drive the resource population to extinction.

In point of fact, any number of wild populations have been harvested to extinction, and many others are currently so depleted as to be considered at risk of extinction. For example, Dulvy et al. (2003) describe 133 instances of extinction of marine populations due to overfishing. How should our model be altered to allow for this possibility?

The Schaefer catch relation $h = qEx$ is predicated on the assumption that the exploited population always distributes itself uniformly over the fishing area – that is the reason why catch rates (per unit effort) are proportional to stock size x , with a constant catchability coefficient q . As explained in Clark (2006, Sec. 2.2), this assumption probably does not hold, even approximately, for most marine populations.

To mention one example, many small pelagic fish species, such as sardines and anchovies, typically form large schools, whose size is relatively independent of the total population size. If these schools are readily located by fishermen, catch per unit effort will remain relatively constant over all population levels (Mackinson et al. 1997).

Thus $h = qE$ may be a more realistic catch equation than the Schaefer equation. In this case the fishery is either economically viable (if $p > c/q$) or not. At low price levels the fishery will remain unexploited, but with higher prices the population will be fished to near extinction under open-access conditions. An example of this process occurred in the world's largest fishery (by weight), the Peruvian anchoveta fishery, in the 1970s (Figure 1.10).

Harvesting of Peruvian anchoveta began in earnest in the 1960s, in response to increasing world demand for fish meal. Following several years of very large catches, the population crashed in 1971-72, partly because of adverse environmental conditions, but doubtlessly also from extremely heavy fishing pressure. While not actually exterminated, the anchoveta population remained at historically low levels until the 1980s. Eventually the stock recovered to provide substantial, if fluctuating, catches.

EXERCISES

1.10 Show that the modified Golden Rule, Eq. (1.45), can be written in the form

$$\frac{dR}{dz} = \delta$$

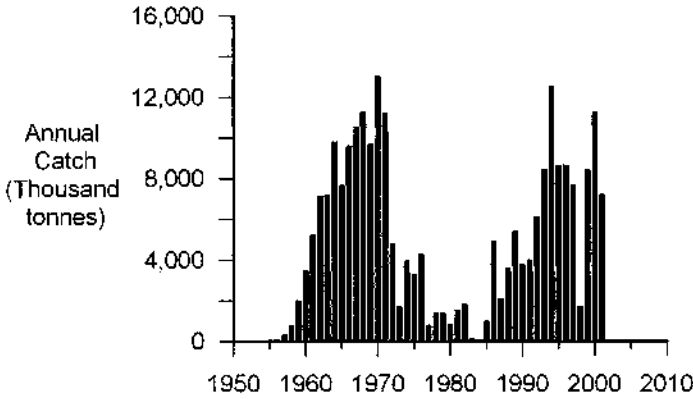


Figure 1.10 Annual catches of Peruvian anchoveta, 1955-2001.

where $R = (p - c(x))G(x)$ is sustainable economic rent and $z = \int_{x_{BE}}^x (p - c(u))du$ is the cash-in value of the resource stock. Suggestion: by the chain rule we have $dR/dz = (dR/dx) \div (dz/dx)$.

1.11 Derive Eq. (1.52) for x^* in the case of the Schaefer-logistic model. Suggestion: note that Eq. (1.45) becomes a quadratic equation in this case. The Schaefer-logistic model has been applied to the Eastern Pacific yellowfin tuna population by Schaefer (1967), who estimated the parameter values

$$r = 2.61 \text{ per annum}, \quad K = 1.3 \times 10^5 \text{ tonnes}$$

Assuming that $x_{BE} = 0.3K$, calculate x^* as a function of the annual discount rate δ . Why is x^* rather insensitive to δ in this example?

1.12 Consider the discrete-time population model $x_{t+1} = F(x_t - h_t)$. Determine the optimal harvest strategy under positive discounting and zero costs. What is the form of the Golden Rule in this case? Suggestion: one approach is to assume a finite time horizon of T years; then use mathematical induction.

1.6 A MODEL OF INDIVIDUAL BEHAVIOR

We next wish to study various possible management techniques for common-property resources. That is, the resource stock in question is assumed to remain common-property (but not necessarily with unlimited open-access), but entirely under the jurisdiction of a central government. A basic aspect of the management of such resources is what economists have called the *principal-agent* problem (Clarke and Munro 1987). The principal (government) wishes to achieve certain socially desirable objectives, but the agents (resource harvesters) have their own objectives, which may conflict with the objectives of the principal.

An additional complication in the case of common-property resources is that the harvesters are in competition among themselves. As we have seen, this competition, unless controlled in some way, leads to overexploitation and the dissipation of economic rents. The question then is, what management techniques are available to the government, that can successfully overcome this so-called tragedy of the commons? It can be stated at the outset that many resource management programs in the past have been far from successful in achieving their stated objectives. In other cases, specified objectives have been met, but the resource industry has not remained profitable. The latter situation, as we shall see, has been common in marine fisheries.

To address these issues we need to be able to predict how resource harvesters will respond to different management strategies. In other words, we need to develop and use a model of individual behavior of resource harvesters. Staying within the setting of marine fisheries, we now describe such a model.

It will be convenient to use daily fishing effort E as our basic individual decision variable:

$$E = \text{individual daily fishing effort} \quad (1.56)$$

How would E be specified, exactly? Imagine the example of a trawler that drags a trawl-net through the water. According to Rothschild (1972) fishing effort should be defined as the volume of water passing through the net per unit time. With this definition, the Schaefer catch equation for daily catch rate h ,

$$h = qEx \quad (1.57)$$

makes good sense: the catch should be proportional to stock size x and to the rate at which sea water is screened E (but recall the earlier discussion). Effort E would then have units m^3/day and catchability would have units m^{-3} .

We suppose that the vessel captain can vary daily effort E up to some limit E_{\max} :

$$0 \leq E \leq E_{\max} \quad (1.58)$$

For example, the number of hours fished per day, the size of the trawl, and the trawling speed, would determine the value of E . For a given vessel there will be a maximum possible daily effort level, E_{\max} .

The daily effort cost $c(E)$ is assumed to be nonlinear, with increasing marginal cost $c'(E)$, as shown in Fig. 1.11. Here c_0 is the *daily mobilization cost*, which is the cost of setting out for a day's fishing. If no fishing takes place ($E = 0$) then no cost is incurred. Thus $c(0) = 0$ but $c(E) \geq c_0$ for all $E > 0$.

Daily net revenue R is given by

$$R = pqxE - c(E) \quad (1.59)$$

Under unregulated open access the fisherman (i.e. the vessel captain) uses the *myopic decision rule*:

$$\left. \begin{array}{l} \text{maximize}_E (pqxE - c(E)) \\ \text{subject to } 0 \leq E \leq E_{\max} \end{array} \right\} \quad (1.60)$$

In other words, we are assuming that the fisherman operates his vessel so as to obtain the largest possible income from each day's fishing. This seems eminently

reasonable – how could he do better than that? When all fishermen do the same thing, of course, they gradually reduce the fish stock x , and this may result in overfishing. So in fact the fishermen might do better by using a lower amount of daily effort – but only if all fishermen agreed to do this, and then adhered to the agreement. Clearly this is unlikely to happen without the help of the government in terms of establishing fishing regulations and then enforcing them.

The solution of our myopic decision rule, Eq. (1.60), involves three cases. First we define E_1 by (see Fig. 1.11)

$$c'(E_1) = \frac{c(E_1)}{E_1} \tag{1.61}$$

Expressed in words, E_1 is the effort level at which marginal effort cost $c'(E_1)$ equals average effort cost $c(E_1)/E_1$. We write c_1 for this common value, and draw the line $y = c_1E$ on our graph, Fig. 1.11. This line is tangent to the cost curve at the point $E = E_1$. Note in addition that

$$E_1 \text{ minimizes average cost } c(E)/E \tag{1.62}$$

Finally, E_1 represents a *shut-down* level of effort, in the sense that it is never optimal to use a positive effort level less than E_1 . To see this, imagine that $pqx < c_1$, so the revenue line $R = pqxE$ in the Figure lies below the tangent line. Clearly $R < 0$ for all positive E , so that the best action is to stop fishing.

Similar considerations show that the solution to the myopic rule is given by

$$\left. \begin{aligned} E = 0 & \quad \text{if } pqx < c_1 \\ c'(E) = pqx & \quad \text{if } c_1 \leq pqx < c'(E_{\max}) \\ E = E_{\max} & \quad \text{otherwise} \end{aligned} \right\} \tag{1.63}$$

We thus obtain the following predictions for the effort level E employed by a competing fisherman under unregulated open-access:

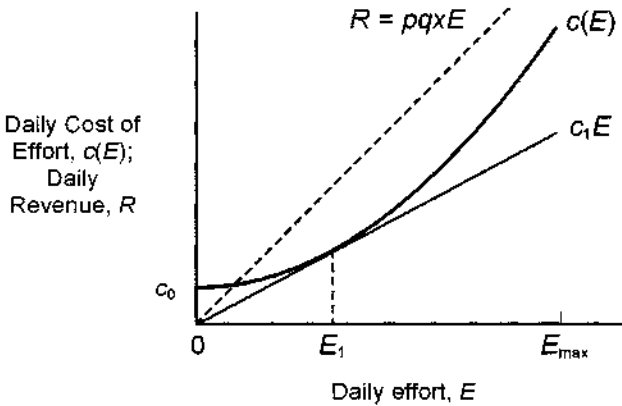


Figure 1.11 Daily effort cost $c(E)$, and daily revenue $R = pqxE$. Effort level E_1 minimizes average cost $c(E)/E$.

1. No fishing takes place if pqx is too small.
2. If fishing does occur then $E \geq E_1$.
3. Effort E is an increasing function of pqx .

Bionomic equilibrium

Suppose now for simplicity that all participating vessels have the same cost function $c(E)$ and the same catchability coefficient q . Provided that $pqx > c_1$ fishing will then take place, gradually reducing the stock x (unless the fleet is too small to achieve this result). An equilibrium will be reached when we have $pqx = c_1$, or $x = x_{BE}$ where

$$x_{BE} = \frac{c_1}{pq} \quad \text{where } c_1 = c'(E_1) \quad (1.64)$$

This is the bionomic equilibrium for the unregulated open-access fishery; compare Eq. (1.31). Note also that at bionomic equilibrium we have $E = E_1$ and

$$R = pqx_{BE}E_1 - c(E_1) = 0 \quad (1.65)$$

by Eqs. (1.61) and (1.64). As in our earlier model, resource rents are entirely dissipated at bionomic equilibrium. (It is worth pointing out here that this prediction is no longer valid if different vessels have different cost functions or catchabilities. We will analyze this case in Chapter 3.)

The TAC method

The undesirability of bionomic equilibrium is the reason that management of a fishery is considered necessary. What form should this management take? Historically, the emphasis has been on preventing overfishing. By limiting annual catches, fishery managers can prevent stock depletion, or in the case of an already depleted stock, can arrange for stock rehabilitation. As mentioned earlier, the usual management objective has been MSY, possibly with a safety factor to allow for the inevitable uncertainties in stock estimates and actual catch levels. The annual catch quota set with such an objective in mind is called the TAC – Total Allowable Catch. Exactly how the TAC should be determined, depending on current estimates of stock size, is a topic of much discussion at the moment (e.g., Walters and Martell 2004).

Supposing that the TAC has been specified, how is it achieved in the fishery? Ideally, the cumulative season's catch is monitored on a daily basis, and the fishery is closed for the year when the TAC has been caught. In some cases, the managers simply open the fishery for a specified period of time, based on estimated catch rates for all participating vessels. Let us ask how these management techniques would affect the decisions of individual fishermen.

Previously we supposed that the individual fisherman (captain) would employ an effort level E that maximizes his net daily revenue. TAC-based management should cause no deviation from this myopic decision. The individual cannot do better than the daily maximum, regardless of how long the fishing season will last.

However, something new does occur. Suppose, to be precise, that the fishery has been at unregulated bionomic equilibrium until now. With the introduction of limited TACs the stock x begins to recover. Hence catch rates $qx E$ start to increase, so net daily revenues R become positive. In addition, the fisherman increases his effort level E – see Fig. 1.11. The fishery moves away from bionomic equilibrium.

Or does it? Once net revenues become positive, other fishermen tend to enter the fishery. The almost universal experience in TAC-managed fisheries has been that an increase in fleet capacity occurs in response to the emergence of positive revenues (Clark and Munro 2002). In order to maintain the TAC, managers are forced to further shorten the fishing season, and this process can sometimes reach extreme limits. For example, the Pacific halibut fishery off the West coast of North America, with area-specific TACs determined by the International Pacific Halibut Commission, is considered well-managed by biological standards. Yet by the 1980s fishing seasons had to be reduced to a few days a year to prevent overfishing by a vastly expanded fishing fleet. (Recently the TAC approach has been supplemented by a system of individual catch quotas, obviating the need for shortened seasons; more on this later.)

Thus, while TAC-based management (using seasonal closures) can protect a fish population and maintain a sustainable fishery, it tends to encourage an excess of harvesting capacity. What if anything limits the expansion of the fishing fleet? Suppose there are N vessels, all alike, and each using daily effort E . The daily catch of the fleet is $Nqx E$. If the fishery is open for T days to catch the TAC, Q , we have

$$NqxET = Q$$

or

$$T = \frac{Q}{Nqx E} \quad (1.66)$$

Season length T is thus inversely proportional to fleet size N .

If the fleet size N is large enough to catch the quota Q then total fleet revenue is, by Eq. (1.66)

$$\begin{aligned} \text{Total fleet revenue} &= NT(pqx E - c(E)) \\ &= \left(p - \frac{c(E)}{qx E} \right) Q \quad \text{where } c'(E) = pqx \end{aligned} \quad (1.67)$$

Note that this is a constant independent of N : the fleet simply shares the same total revenue, no matter how many vessels take part. By shortening the fishing season as necessary, the managers maintain a fixed TAC Q .

Annual net income per vessel, R_{annual} , thus equals $(1/N)$ times the above expression. New vessels will enter the fishery if this revenue covers the annual interest on capital, i.e., if

$$R_{\text{annual}} \geq ic_f$$

where c_f is the capital cost of a vessel and i is the annual rate of interest. From this and Eq. (1.67) we deduce the ultimate fleet size for an open-access, TAC-regulated

fishery:

$$N_{OA} = \left(p - \frac{c(E)}{qxE} \right) \frac{Q}{ic_f} \quad (1.68)$$

Parameter sensitivities in this expression all make good sense: larger values for p , x or Q imply larger fleets, while larger values for i or c_f imply smaller fleets.

The main point of this discussion, however, is that under our present assumptions of TAC-based management and unlimited access, a new “regulated bionomic equilibrium” (Homans and Wilen 1997) emerges, characterized not by overfishing but by an unnecessarily large fleet, short fishing season, and zero net economic benefits (when fixed costs are taken into account). It is apparent that this outcome is not in any way optimal. Many recommendations for redesigning fishery management systems to avoid overcapacity of fishing fleets have been made. Recently the need to explicitly recognize and manage the economic incentives of resource exploiters (fishermen) has been clearly identified (Hilborn et al. 2005; Grafton et al. 2006; Beddington et al. 2007).

Before discussing incentive management, however, let us first consider another popular management tool, called Limited Entry. This term means that a fixed number N of fishing licenses are awarded; nonlicensed vessels are strictly excluded from the fishery. How do the licensed fishermen now determine their optimal daily effort levels E ?

As before, it is clear that limited entry will have no effect on the licensed fishermen’s daily behavior (unless N is very small). They will still choose effort E to maximize daily net revenues R . As the fleet size N is reduced, the fishing season will last longer and licensed fishermen will therefore enjoy positive net incomes, $RT > ic_f$. (Which fishermen obtain licenses, and which are denied, is of course a difficult matter, usually decided on the basis of historical participation in the fishery. Sometimes excluded fishermen are paid compensation for removing their vessels; see Chapter 4.)

Thus the combination of TACs and limited entry would seem to finally resolve the tragedy of the commons in a commercial fishery. Unfortunately it’s not that simple! We also need to consider a further phenomenon that regularly occurs in limited-entry fisheries, known as “effort creep.”

Effort creep

A typical example of effort creep occurred in British Columbia’s sablefish industry, which became a limited entry fishery in 1981, with 48 licensed vessels. But the limited entry program did not resolve the problem. In an attempt to increase fishing power, vessel owners switched to larger boats, added extra gear and navigation aids, and so on (Turris 2000).

To include such behavior in our model, suppose that by means of an expenditure w the vessel owner-captain can reduce his effort-cost function $c(E, w)$ and/or increase his daily maximum effort level $E(w)$. Net annual revenue then becomes

$$R(w) = T(pqx E - c(E, w)) - iw$$

For any value of w , the captain will determine E to maximize daily net revenue as before – see Eq. (1.63). This will imply an increase in daily effort, relative to the situation prior to vessel upgrading. Instituting limited entry in a fishery increases annual revenues for the licensed fishermen, and this motivates them to try to capture a larger share of the benefits. It's the same logic as before: positive rents in a common-properly resource attract additional harvesting effort, either in terms of new entrants or through capacity enhancement among licensed participants.

By 1989 the B.C. sablefish industry was verging on bankruptcy. The Canadian government and the industry then agreed to try a new management approach based on individual catch quotas, which were introduced in 1990. We will discuss this method below, after discussing the question of overall optimization.

Optimal fishing

It is always useful to consider the question of over-all optimization, at least as a point of comparison. Here we will assume that a certain sustained population $x = x_{\text{opt}}$ has been selected by the managers. What is the economically optimal harvesting regime, with $x = x_{\text{opt}}$, in terms of fleet size N , individual vessel effort E , and season length T ? (For simplicity we continue to ignore intra-seasonal variation in x .)

First treating N as a parameter, we can formulate our optimization problem as follows:

$$\underset{E, T}{\text{maximize}} NT(pqx E - c(E)) \quad (1.69)$$

subject to

$$0 \leq E \leq E_{\text{max}}, \quad 0 \leq T \leq T_{\text{max}} \quad (1.70)$$

$$H = NTqx E \leq Q \quad (1.71)$$

where Q is the TAC. (Once this problem has been solved, we can then determine the optimal fleet size N .)

Suppose first that the TAC Q is in fact caught before the season's end T_{max} . Then $H = Q$, so

$$T = \frac{Q}{Nqx E}$$

After substitution, Eq. (1.69) becomes

$$\underset{E}{\text{maximize}} \left(p - \frac{c(E)}{qx E} \right) Q \quad (1.72)$$

and this is the same as

$$\underset{E}{\text{minimize}} \frac{c(E)}{E} \quad (1.73)$$

Thus optimal effort minimizes average daily cost $c(E)/E$. Thus $E = E_1$ as shown in Fig. 1.11. Therefore, according to Eq. (1.63), which also applies to a TAC-managed fishery, individual vessel (myopic) effort E used by competing fishermen is larger than the overall optimum E_1 . Excessive, often extremely excessive levels of effort

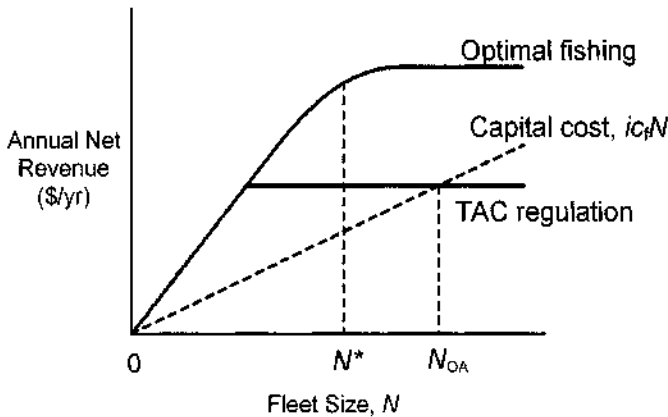


Figure 1.12 Total annual revenue from optimal fishing (upper curve), and under TAC-based management (lower curve).

are in fact characteristic of the TAC-managed fishery, which has sometimes been called a “derby fishery” for this reason.

Figure 1.12 shows the optimal fleet annual revenue (except for capital costs) as a function of fleet size N . This reaches an upper limit for large N (the fleet just divides up the maximum total revenues). The dashed line depicts amortized capital costs, and the optimal fleet size N^* can be read off the figure.

The figure also shows total annual fleet revenue for the TAC-managed fishery; for large N this is given by Eq. (1.67). Fleet size N_{OA} under open access occurs where revenue equals amortized capital cost, i.e., at regulated bionomic equilibrium.

Here is a review question: What would happen, in terms of Fig. 1.12, if a limited entry program reduced N from N_{OA} to N^* ? Would the optimum be achieved? Re-read the section on effort creep if you have forgotten this.

A possible response to the foregoing discussion is that surely the managers of a fishery can introduce regulations that will prevent effort creep. Such regulations are in fact often attempted. Restrictions on fishing gear, on vessel size, weight and horsepower, on the number of days spent fishing per week and so on, are commonplace. One problem, of course, is that such regulations are usually brought in only after their need has become recognized because of past effort creep. But the main difficulty stems from the fact that these regulations do not alter the economic motivations of fishermen, which are to do whatever is necessary to maximize their short-term gains. The next section addresses this issue.

EXERCISES

1.13 Prove that E_1 as defined by Eq. (1.61) indeed minimizes average effort cost $c(E)/E$.

1.14 Sketch a graph of myopically optimal effort E as a function of the return to effort pqx . Is the discontinuity intuitively reasonable? How does it depend on mobilization cost c_0 ?

1.15 Discuss the sensitivity of open-access fleet size N_{OA} (Fig. 1.12) to economic parameters.

1.7 INDIVIDUAL VESSEL QUOTAS

We have modeled individual fishermen’s behavior under three situations, unregulated harvesting, open-access TAC-regulated harvesting, and TAC-regulated harvesting with limited entry. All three lead to similar long-term outcomes, namely the dissipation of economic benefits through overfishing and overexpansion of fleet harvesting capacity. TAC-based management at least has the effect of protecting the resource from overexploitation, although this can prove difficult if fishing capacity is large. The source of the problem lies in individual fishermen’s economic incentives under conditions of competitive access to the resource.

One possible way to overcome common-property resource problems is through privatization. The private owner of a resource stock usually has a strong incentive to preserve it – although our discussion of discounting shows that this may not be universal. Private ownership of land-based resources is common in most countries today (but see de Soto 2000), and some economists have recommended that private ownership be extended to other resources, including marine fisheries (e.g., Scott 1955). Except for sedentary species such as shellfish, however, this suggestion has seldom been implemented. Many marine populations exist or migrate over huge areas of the ocean, and privatization is plainly not feasible in such cases.

So what, if anything, can be done to improve our use of common-property renewable resources, specifically marine fish populations? In the late 1970s, doubtlessly as a consequence of the recent establishment of 200-mile fishing zones worldwide, several economists suggested that individual annual catch quotas (IQs) might operate as proxies for private ownership, without requiring actual privatization. We next use our behavioral model to investigate the effect that such individual quotas could have on fishermen’s decisions.

Assume now that each fisherman is awarded an individual annual catch quota Q . These quotas are strictly enforced, to the extent that quota “busting” is effectively discouraged (this is of course extremely important!). The fisherman will then attempt to maximize his annual net revenue. Once again ignoring changes in the stock x over the season, this becomes

$$\underset{E,T}{\text{maximize}} T(pqx E - c(E)) \tag{1.74}$$

subject to

$$0 \leq E \leq E_{\max}, \quad 0 \leq T \leq T_{\max} \tag{1.75}$$

$$H = Tqx E \leq Q \tag{1.76}$$

Here E again denotes daily effort (the same for each day) and T denotes the number of days that the fisherman goes fishing during the year. We again assume that the fish stock x remains approximately constant over the fishing season. While rather unrealistic, this assumption simplifies the analysis.

There are two things to notice about this new optimization problem. First, though similar in appearance to our myopic decision model of Eqs. (1.60), the new case is definitely not myopic. The fisherman must now determine both his optimal daily effort level E and the number of days T that he will fish for the whole year. These are linked by the quota constraint $H = Tqx E \leq Q$, and this makes all the difference! Remember, the myopic decision model also applies to TAC and limited-entry fisheries. Now for the first time we have something different.

Second, the new problem is mathematically identical to our whole-fishery optimization model, Eqs. (1.69)-(1.71). This suggests that individual catch quotas might result in optimal behavior by the fisherman without further management intervention. However, this is getting ahead of the story. For example, how should the individual quotas Q_i be allocated among the fishermen? We take up this question after discussing the solution to the above model. (Here we present the complete solution, not just the partial solution given earlier.)

Our problem, Eqs. (1.74)-(1.76), is a two-variable maximization problem with three constraints, not counting the non-negativity constraints. We first assume that

$$pqx > c_1 = c'(E_1) \quad (1.77)$$

so that the fishery is economically viable. See Fig. 1.11, and recall that E_1 minimizes average cost. Recall also that the solution to the myopic decision problem is $E = E_0$ where E_0 maximizes daily net revenue $R = pqxE - c(E)$. Therefore

$$\left. \begin{aligned} c'(E_0) &= pqx && \text{if } pqx < c'(E_{\max}) \\ E_0 &= E_{\max} && \text{otherwise} \end{aligned} \right\} \quad (1.78)$$

The fisherman will never use effort $E > E_0$ because this would reduce daily income with no offsetting gain. As we will see, however, the optimal effort when the fisherman has a yearly catch quota Q may well be less than E_0 .

To describe the solution to our constrained maximization problem, we consider two cases.

Case 1. Large annual quota Q .

If the fisherman used E_0 for the whole year, his catch would be $H = H_0$ where

$$H_0 = qx E_0 T_{\max} \quad (1.79)$$

If Q is larger than this, the fisherman will do best by catching H_0 and leaving the rest of his quota in the sea. Therefore:

If $Q > H_0 = qx E_0 T_{\max}$ then

$$\begin{aligned} E &= E_0 \\ T &= T_{\max} \\ H &= H_0 \\ RT &= (pqxE_0 - c(E_0))T_{\max} = \left(p - \frac{c(E_0)}{qx E_0}\right) H_0 \end{aligned}$$

where RT is the year's net revenue.

Case 2. Small annual quota Q .

If $Q \leq H_0$ the fisherman will catch his quota:

$$H = qxET = Q$$

With this condition, our optimization problem becomes

$$\underset{E}{\text{maximize}}(pqxE - c(E)) \frac{Q}{qx E}$$

or

$$\underset{E}{\text{maximize}} \left(p - \frac{c(E)}{qx E} \right) Q$$

and this reduces to

$$\underset{E}{\text{minimize}} \frac{c(E)}{E} \tag{1.80}$$

(The constraints $E \leq E_{\max}$ and $T \leq T_{\max}$ still apply.)

Now, effort level E_1 minimizes average cost $c(E)/E$, so E_1 is optimal if this effort results in catching the quota Q within the season, i.e., if $qx E_1 T_{\max} \geq Q$. Therefore

If $0 < Q \leq H_1 = qx E_1 T_{\max}$ then

$$\begin{aligned} E &= E_1 \\ H &= qx E_1 T = Q \\ T &= Q / qx E_1 \\ RT &= (pqxE_1 - c(E_1))T = \left(p - \frac{c(E_1)}{qx E_1}\right) Q \end{aligned}$$

In other words, with a small annual quota Q , the fisherman does best by minimizing average daily effort cost, using $E = E_1$. Recall that

$$E_1 < E_0$$

so this harvest strategy is not myopic.

What actually happens when IQs are first introduced into a fishery is often quite spectacular. The derby fishery, with intensive fishing over a short opening is immediately transformed into a more gradual affair, as the fishermen switch from a

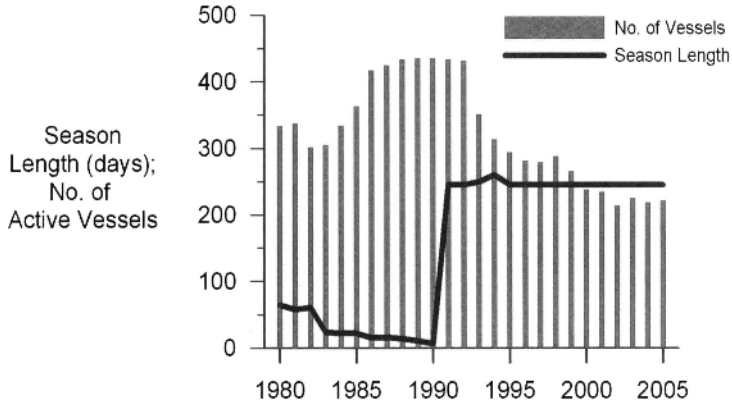


Figure 1.13 Pacific halibut fishery (British Columbia): season length and number of active vessels, 1980-2005. IQs were introduced in 1991. (An annual fishing season of 245 days is set by the IPHC, to protect migrating or spawning halibut.) From Munro et al. (2009).

myopic, high-effort strategy to a more efficient use of their vessels (Fig. 1.13). Other changes also occur; for example, safety at sea often improves because fishermen can now afford to stay home when weather conditions are bad. (In our model T denotes the number of days spent fishing per year, but these days do not need to be contiguous. The fishermen can take weekends off or stay home on rainy days, just like everyone else – a luxury they could not afford in a derby fishery.) Also, product quality may improve as fishermen take more care in handling the fish. This in turn can increase prices obtained for the fish, further enhancing fishermen’s incomes. All these changes, and others to be discussed later, stem from the altered incentives that result from individual quotas.

We have yet to complete the solution of our constrained maximization problem. Since $E_1 < E_0$ we have $H_1 < H_0$, so we need to consider the case that $H_1 < Q < H_0$. Effort level E_1 is not large enough to catch the quota Q in time T_{\max} , so that a larger effort E is needed, with $qxET_{\max} = Q$. Thus:

If $H_1 \leq Q < H_0$ then

$$\begin{aligned} E &= Q/qxT_{\max} \\ H &= Q \\ T &= T_{\max} \\ RT &= (pqxE - c(E))T_{\max} = \left(p - \frac{c(E)}{qxE} \right) Q \end{aligned}$$

The complete solution is depicted in Fig. 1.14. The above analysis indicates that IQs can motivate fishermen to use efficient harvesting schedules over the year (or other quota period), and this can alleviate the problems associated with a derby fishery, at the same time increasing the fishermen’s annual net incomes.

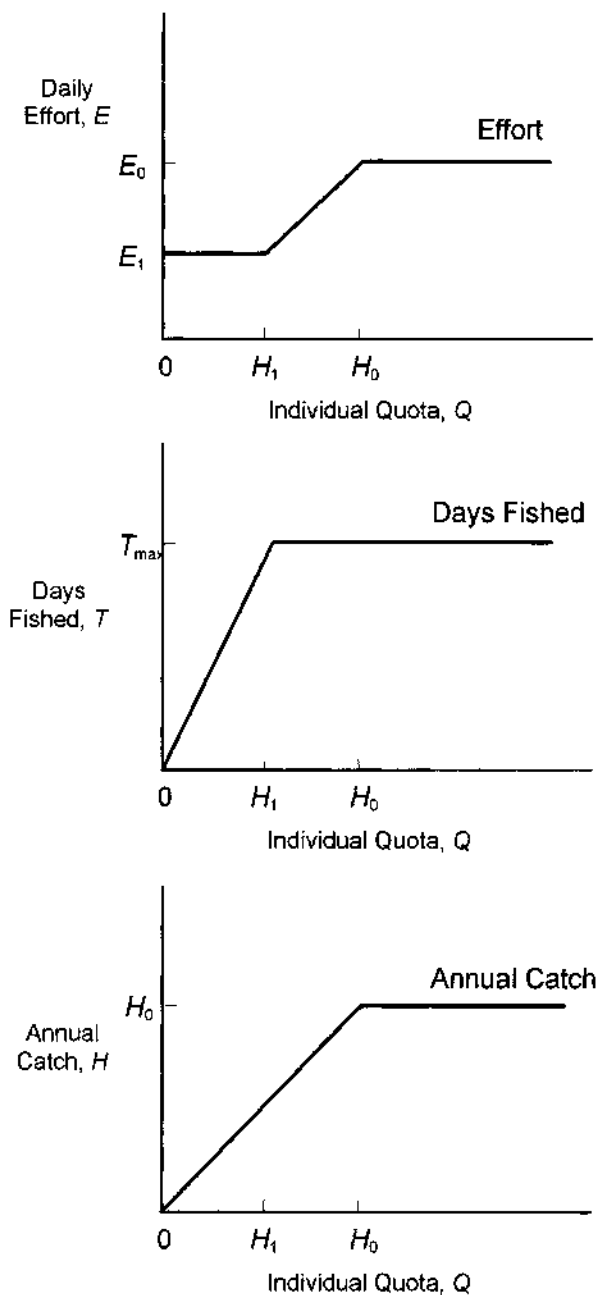


Figure 1.14 Fisherman daily effort, days fished and annual catch under individual annual catch quota Q . (All graph segments are linear.)

Other questions also need to be addressed, however. For example, what is the optimal allocation of the TAC among the fishermen? What if some fishermen have more (or less) quota than they prefer? How are the annual TAC, and the corresponding individual quotas, adjusted in response to natural fluctuations in the resource stock? Would individual effort quotas be equivalent to individual catch quotas, or would one method be superior to the other?

First, we consider the question of optimizing the allocation of individual catch quotas Q_i . Suppose, for example, that the existing fleet consists of a large number N of vessels (again assumed to be identical, for simplicity). The TAC now is denoted by Q . Should each vessel get an equal share $Q_i = Q/N$, or would it be better to eliminate some vessels entirely and spread the TAC among fewer vessels? To answer this question, let $c_h(Q_i)$ be the cost for a vessel to harvest its annual quota Q_i using the optimal effort strategy. (The function $c_h(Q_i)$ can be deduced from the above equations, but we do not need to do so here.) If the TAC is divided equally among the fleet of N vessels, then the total fleet cost for a year will equal

$$Nc_h(Q_i), \quad Q_i = Q/N$$

Alternatively, suppose that these quotas Q_i are pooled into groups of size n , which are allocated to N/n vessels, the remaining vessel being kept idle. (Forget about fairness for the moment – we'll return to that question later.) Total fleet annual cost is then

$$\frac{N}{n}c_h(nQ_i)$$

We wish to determine n to minimize this expression. Since N is fixed, this is the same as minimizing

$$\frac{c_h(P)}{P}$$

where $P = nQ_i$ is the size of a pooled quota. In other words, the optimal quota P minimizes average individual vessel harvesting cost for the season. If the initial fleet size N is large, this could imply a major change in the operation of the fishery. (A numerical example is given in the Exercises.) Failure to reallocate quotas in a near-optimal fashion could negate most of the potential gains from the IQ system.

The next question is, how can fleet reduction be done in a way that is fair to the "losers," and at the same time is economically efficient? A popular method that has been widely used is to employ government funds to buy out the surplus vessels. Buy-back payments, however, have seldom been effective in controlling overfishing (Holland et al. 1999; Weninger and McConnell 2000). Such payments may temporarily reduce the capacity for overfishing, but they do not alter the underlying economic incentives (Clark et al. 2005). We discuss this topic further in Chapter 4.

Transferable quotas

If buybacks (analyzed in Chapter 4) are out, what else is there? In fact, buybacks may be completely unnecessary in an IQ system, if *quota trading* is allowed. Each

fisherman will realize that he could benefit from owning a larger quota, even if he has to buy the extra quota from another fisherman. And some fishermen may be willing to sell their quotas and leave the fishery, if the price is right. We can predict that a market will become established for the trading of quotas, in whole or in part. This is exactly what has happened in many ITQ (Individual Transferable Quota) fisheries. Figure 1.13 shows relevant data for the B.C. Pacific halibut fishery, which was placed on an ITQ management system in 1991. Annual TACs in this fishery have ranged from 2,721 to 5,924 tonnes over the period depicted. Total landed value has varied from \$13.8 million (in 2005 Canadian dollars) to \$50.4 million. (We discuss variations in the TAC below.)

The ex-vessel price of halibut has varied between \$4.13 and \$10.40 per kilogram over the same period, with an increase trend of about 3.5%/yr. A large part of this increase seems to have been due to increased quality of the product (fresh fish instead of frozen) following the introduction of ITQs (Herrmann 1996). There has been no buyback program in this fishery. (We model the market for tradeable quotas in Chapter 3.)

As in most fisheries, halibut stocks experience considerable annual variability. In particular, halibut TACs vary from year to year, meaning that individual quotas must also vary. In practice, what vessel owners possess is not a fixed annual catch quota, but a specified share of the year's TAC. But the halibut fishermen are presumably capable of handling such fluctuations; at least they can be fairly certain that their annual share will actually be available for harvesting.

Such is not the case in some fisheries. For example, annual stock levels in some short-lived species are highly variable, and may be difficult if not impossible to predict. (Most squid populations have this characteristic, for example.) TACs cannot be realistically determined in such cases, and there would be no basis for setting IFQs either

An alternative method using individual effort quotas might be useful under these circumstances. Indeed, some fishery scientists recommend individual effort quotas over individual catch quotas in general, on the grounds that effort quotas are not dependent on accurate stock assessments, which are often difficult to achieve. Depending on how they are administered, however, individual effort quotas may encourage effort creep (unlike individual catch quotas). We discuss this question further in the next section.

Conservation incentives

An important aspect of ITQ systems not encompassed by the above model, is their potential for generating strong support among the fishermen for resource conservation. The fishermen recognize their quotas as valuable assets, enabling them either to earn a decent living from the fishery, or if they so prefer, to sell out and withdraw from the fishery. The market value of quotas reflects the present value of expected future revenues from using the quota. Obviously this value will be enhanced if the fish population is protected. Therefore ITQ fishermen will favor a management strategy that maximizes the total present value of current and future

harvests. This incentive is notably lacking in the case of fisheries that are managed without individual quotas.

Experience with ITQ programs in many countries support this idea. ITQ fishermen typically recommend TACs that are conservative (sometimes more so than those proposed by the fishery biologists). They also agree to help finance stock assessment and other research activities. Examples of this and other types of behavior are discussed in Clark (2006).

Because of their advantages over other methods, ITQs are being increasingly applied in fisheries management. Canada, Norway, Iceland, Australia, New Zealand and Namibia are among the nations that now use ITQs widely. See Grafton et al. (2006) and Beddington et al. (2007) for further discussion.

This is not to say that ITQs by themselves are sufficient for fully effective management of marine fisheries. Indeed, they are still somewhat controversial. The main complaints are, first that ITQs are primarily limited to single-species fisheries, whereas all fish populations are components of marine ecosystems that can be severely impacted by large-scale removals of one or a few species. Second, an ITQ system, being based on TACs, may not take account of the inevitably large uncertainties associated with the marine environment. Finally, by assigning the entire economic rents from a fishery to a selected group of fishermen, ITQs may amount to a give-away of public resources.

We will not attempt to discuss all these issues in this introductory chapter (but see the next section). Regarding the question of resource give-aways it is worth noting that this is not a necessary feature of ITQs. In other examples of publicly owned resources, such as national forests and offshore oil deposits, governments impose substantial royalties on resource harvesters. There is no reason, other than industry resistance, why such royalties cannot be obtained from fisheries also.

ITQs and stock dynamics

The model of individual quotas used above was entirely static – the stock level x was taken to be given and constant. In real life the fish stock will change, both in the short term (within the year) and the long term (inter-annually). Let us continue to ignore short-term changes for now, but let us think about long-term changes. Annual TACs are assumed to be set by the managers, based on recommendations of the ITQ owners. What will these owners recommend?

Consider the case of a depleted stock, in the sense that annual net revenues would be larger at a higher stock level. Would the ITQ owners prefer stock rehabilitation, and at what rate?

The value of quota shares is determined by the present value of future revenues,

$$PV = \sum_{t=0}^{\infty} \frac{R(x_t, h_t)}{(1+i)^t} \quad (1.81)$$

Here R denotes net fleet income in year t , with annual harvest (TAC) h_t and stock level x_t . Stock dynamics depend on the annual harvests:

$$x_{t+1} = G(x_t - h_t) \quad (1.82)$$

where G now denotes the annual natural growth function. The details of discrete-time dynamic optimization are discussed in Chapter 2; the results are analogous to those presented in Sec. 1.4. As before there is an optimal equilibrium stock level x^* , determined by a golden-rule equation. As usual x^* depends on all model parameters, in particular the discount rate i . Higher discounting implies lower preferred stock levels x^* .

Thus the long-term stock level preferred by fishermen will depend on their personal discount rates (which are usually referred to as time-preference rates; see Chapter 3). But what if different fishermen have different time-preference rates? For any given harvest strategy $\{h_t\}$ the present-value expression (1.81) is a decreasing function of the discount rate i . In other words, people with low time preference rate value long-term assets more highly than people with high rates. A quota owner with a high time-preference rate would tend to “cash in” his asset by selling the quota to someone having a lower time-preference rate. Since ITQs are by definition transferable, there will be a tendency for quota shares to accumulate in the hands of low time-preference-rate individuals. Although this is sometimes depicted as an undesirable trend (“the rich get richer”), it does have favorable conservation consequences – a majority of ITQ owners will favor resource conservation policies, such as stock rehabilitation. Such behavior has in fact been noted in several ITQ fisheries (Clark 2006, Ch. 6).

The question remains, for a depleted stock how rapid should the recovery be? Recall that the bang-bang strategy, with $h = 0$ until x recovers to the optimal equilibrium x^* , is economically optimal under our model assumptions. What are these assumptions? The main one is that the ex-vessel price of fish p is a constant, independent of the annual catch h . This might be true for a small fishery selling into a large market, but not for a large, or specialized, fishery (see Chapter 3). If the assumption is not true, i.e., if price p goes up when output h is low, then the bang-bang strategy is no longer optimal. The fishery should not be shut down during stock rehabilitation, but operated at a reduced catch level, taking advantage of higher prices when harvests are small.

A second reason that a gradual recovery strategy might be preferable to the bang-bang strategy is that the fishermen may consider a zero annual income to be an intolerable sacrifice! As with most economic models, we have assumed that costs are in fact opportunity costs. The cost of effort cE includes (among other things) the opportunity wages of captain and crew. The term “opportunity wages” refers to the wages that could be earned in one’s most remunerative alternative employment. This is obviously a tricky concept – do fishermen actually have equally attractive alternative employment opportunities? If not, they will prefer a gradual recovery strategy that provides some positive income.

Finally, there may be considerable doubt that the proposed recovery plan will actually work. Recovery of severely depleted fish populations may never occur,

or may occur only very slowly (Hutchings 2000). Being difficult to deal with, uncertainty in resource management was largely neglected until quite recently. However, the importance of uncertainty is increasingly being recognized, and practical techniques for handling uncertainty are now being developed. We discuss these questions briefly in the next section, and more fully in Chapter 7.

EXERCISES

1.16 Consider a fishery with TAC $Q = 10,000$ tonnes per year. There are $N = 100$ identical vessels, each with a catch quota of 100 tonnes. The cost of catching J tonnes of fish is

$$c_h(J) = c_1 + c_2 J^2$$

where $c_1 = \$20,000$ and $c_2 = \$0.22/\text{tonne}^2$. Determine the optimal pooled quota, and calculate the total cost of harvesting the TAC without, and with optimal pooling. Where do most of the savings come from? Repeat for $N = 200$.

1.17 Continuing with problem 1.16, suppose that the total ex-vessel value of the TAC is \$2.2 million. What is the annual net income per vessel (for N vessels) with no pooling and with optimal pooling? Speculate as to how a pooling strategy might work out in practice.

1.8 THE VEIL OF UNCERTAINTY

Our theory of resource management so far has employed a particularly dubious assumption, namely perfect knowledge. Although our models allow resource stocks to vary over time, they are assumed to do so in a deterministic and completely predictable fashion. For marine fish populations this assumption is highly unrealistic. Not only do these populations fluctuate unpredictably, but in addition determining the current stock size (x in our models) is often extremely difficult simply because the population is never directly observed, but only sampled (either by the fishery, or by independent scientific surveys, or both). Fishery scientists have developed sophisticated statistical technique for estimating stock size (Quinn and Deriso 1999; Walters and Martell 2004), but it has become increasingly evident that even the best – and most expensive – methods usually have wide confidence intervals.

How can TACs be confidently determined under such conditions? And what about ITQs, which clearly require TACs? The 1991 collapse of Canada's Atlantic cod fishery, which had been considered one of the world's best-managed fisheries, greatly reduced scientists' confidence in their ability to manage using the TAC approach (Canada actually had a vessel-quota system). On the other hand, the Pacific halibut fishery has been well managed, using TACs, since the 1930s. This is not the place to discuss the possible reasons for these outcomes. What is clear it that fishery managers throughout the world have been forced to take a much closer look at uncertainty and its implications for management. This applies also to many resources other than fisheries, not the least important being the very atmosphere and

the oceans on which all life depends. Ludwig et al. (1993) make the following suggestions (among others) for improving resource management:

1. Human behavior, as a response to economic incentives, should be included in resource models.
2. Uncertainty should be explicitly recognized in determining harvesting strategies.

These suggestions are addressed throughout this book.

EXERCISES

1.18 List several other sources of uncertainty that might be important in fisheries management.

1.9 OTHER RESOURCES

The fishery models described in this chapter illustrate four important aspects of resource management:

1. Overexploitation of open-access resources.
2. Tradeoffs between current and future benefits.
3. Dynamic optimization models.
4. Incentive management through individual harvest quotas.

Clearly these questions are generally important in renewable resource management. For example, overexploitation has occurred widely in many land-based resources such as forests, grazing lands, and wildlife. As Robert Frost says, "Good fences make good neighbors" – resource owners (i.e., land holders) tend to protect their lands and use their resources wisely. Conversely, users of commonly owned (or un-owned) resources have little incentive for conservation, unless specific management institutions are formed to control exploitation.

But fences (private ownership) are not always feasible, or if feasible may not be considered desirable. For example, in North America and elsewhere large land areas are publicly owned in the form of national and regional parks and forests. All forms of wildlife within these parks are also public property. Conflicts sometimes arise between lethal uses (hunting, logging) of these resources and non-lethal uses (aesthetic pleasure). Lethal uses – harvesting – are controlled by such methods as hunting seasons, bag limits, and timber sales.

Allocating public resources between lethal and nonlethal uses will always be controversial. For example, how many acres of old-growth forest in California should be left unlogged to protect spotted owls? Should brown bears in Alaska be hunted for maximum sustained yield, or should they be protected? No amount of science, or mathematics, or even economics can answer these questions.

But to the extent that public, or any, natural resources are allocated to commercial exploitation, the kinds of bioeconomic models discussed in this chapter can be applied, if suitably modified. To mention one classical example, the age at which trees should be harvested is a bioeconomic question. Not surprisingly, the answer turns out to be highly sensitive to the discount rate; see Chapter 2.

CHAPTER SUMMARY

The dynamics of conservation

The conservation of biological resources is inherently a problem in dynamic optimization. Current harvesting, while profitable in the short run, may reduce the resource stock and result in lower harvest rates in the future. Thus there exists a tradeoff between present and future harvesting of the resource. Resource management attempts to optimize this tradeoff, according to some specified criterion of optimal harvesting.

Why is resource management necessary?

Whenever a valuable resource stock is harvested competitively without any effective centralized management, the outcome is almost invariably overexploitation. The resource stock may be reduced to a fraction of its natural abundance, and in extreme cases destroyed entirely. This outcome, which has been called the “Tragedy of the Commons” (Hardin 1968), can be attributed either to the absence of private ownership of the resource, or to lack of government control. Privatization of resource ownership (which is the norm for land resources, at least in Western economies) can result in conservation, but this possibility may not be feasible for some resources, such as marine fisheries. But whether privately or publicly owned, a biological resource stock still needs to be managed correctly to achieve long-term sustainable and profitable harvests. How to ensure this outcome in practice is the subject of this book.

MSY – pros and cons

The traditional objective of biological resource management has usually been maximum sustained yield, or MSY. Indeed, MSY is often touted as the obvious, uniquely correct criterion for renewable resource management. What could be more desirable than the maximum harvest, especially if sustainable? Management of a biological resource for MSY certainly precludes overexploitation, regardless of circumstances.

At least three difficulties with the MSY concept can be identified:

1. MSY is not necessarily the most profitable use of a resource.
2. For a naturally fluctuating resource, almost no annual harvest level may be sustainable during periods of low resource abundance.

3. For a resource that is harvested competitively (for example, a fishery), harvest regulation based solely on MSY often leads to overcapacity and near-zero profitability.

These difficulties, which are of great practical importance, are discussed throughout the book.

Capital and Investment

Any natural resource stock can be conceived of as a capital asset – “natural capital.” The success of any modern economy is entirely dependent on its stocks of capital, including human capital, manufactured capital, and natural capital. (According to Peruvian economist Hernando de Soto (2000), failure to fully recognize this fact is the main reason for the persistent failure of economic systems in third-world and former Communist countries.) This has two extremely important implications:

1. The economic theory of capital and investment is fully relevant to renewable resource management.
2. Failure to manage natural resources for optimal economic benefits can seriously harm an economy. Mismanagement has sometimes resulted in the collapse of important resource populations.

The present-value criterion

It is widely agreed that the correct criterion for evaluating economic prospects over a long time horizon is the discounted present value of net economic benefits (Mishan and Quah 2007). The only point of contention is the value of the discount rate to be used in the evaluation. This is an important matter, given that the discount rate is often critical in terms of determining the optimal strategy.

For public projects (including resources), the “social” discount rate is appropriate, and considered to be close to the real (inflation-adjusted) rate of interest on government bonds, say 3-5% per annum. As we see throughout the book, discount rates higher than this can have devastating anticonservationist implications for resource management.

Bioeconomic models

Chapter 1, like the rest of this book, uses relatively simple dynamic bioeconomic models as a basis for comprehending important issues in resource economics. Complex computer models are left to the specialist literature. The models used in this chapter, though fairly simple, are often quite subtle because of the interplay between biology and economics, a topic that is widely misunderstood. (Look in vain for economic insights in textbooks on fishery management, for example.)

Our basic bioeconomic model, Eqs. (1.36)-(1.41), for example, provides an incisive explanation of open-access overexploitation, in contrast to the economic

optimum. It also explains convincingly the roles of biological parameters (growth rate, carrying capacity) and economic parameters (price, cost, discount rate) in determining the optimal harvest strategy. The basic model, which is linear in the control variable, prescribes a “bang-bang” adjustment strategy for approaching the optimal equilibrium stock level. But this result is model-dependent, and does not remain valid under alternative assumptions. These important details are discussed in later chapters.

Behavioral models

One of our main interests will be resource management and regulation (Chapter 5). Here an important question is to predict the responses of resource harvesters to various types of regulation. Unless these responses are predictable, at least in qualitative terms, resource management programs are likely to have unintended consequences. A notorious example of this has dominated fishery management for many decades. I refer to the all but universal emergence of overcapacity of fishing fleets in managed fisheries. For example, the European newsletter *El Anzudo* for June, 2009, in an article on the European Common Fisheries Policy (CFP), stated that overcapacity of fishing fleets continues to be a major problem in European fisheries, resulting in persistent overfishing and suboptimal economic performance.

Such overcapacity, which is completely predictable from bioeconomic models (Chapter 5), seems to have taken fishery managers by surprise. (Of course overcapacity often appeals to politicians, because it implies extra, if non-productive, employment.)

Our model of fishermen’s behavior, Sec. 1.6, generates a fundamental principle of resource bioeconomics. Specifically, the use of individual harvest quotas can completely alter the economic incentives of harvesters, leading to improved resource conservation. Individual quotas are not full property rights, but they do possess many of the desirable features of such rights, including the encouragement of sustained and efficient harvesting. Chapter 5 discusses resource regulation in more detail.

Important topics omitted, or only lightly touched upon, in this chapter, include

- externalities
- game theory
- investment strategies
- uncertainty
- ecosystem dynamics

These topics will be taken up in later chapters.

