Fisheries and aquaculture economics

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FISHERIES AND AQUACULTURE ECONOMICS

Fisheries and Aquaculture Economics
2nd edition

ISBN 978-87-403-2281-1
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PREFACE

This book is the result of many years' experience of teaching fisheries economics and management, also called bioeconomics, for undergraduate and graduate students in interdisciplinary programs, both in Norway and abroad. These students often have a limited background in economics and mathematics and the challenge has been to be analytical without being unnecessary mathematical. I have found that with the exercises at the end of some of the chapters students are quite capable looking at fisheries economics and management from an analytic perspective. Exercises and careful reading of the logical steps of the text is the key to understanding fisheries economics.

For the 2018 edition, I decided to expand the subjects considerably by including another part, with four chapters, on aquaculture economics. Aquaculture production of fish, including shrimp and other marine organisms, have been on the rise globally for some decades, and in 2014 surpassed that of capture fisheries. Thus, I felt it timely to do this now. The aquaculture economics part, chapters 11–14, can be studied without reading the preceding fisheries chapters. Nonetheless, I recommend all students to read Chapter 1 Introduction. In Chapters 11–14, there are some references to material in the fisheries part, and I recommend you to have a look, if you have not seen it before or want a brush up. The aquaculture chapters comprise more empirical materials than the fisheries part. I trust the combination of graphs, tables and theory will be useful to aquaculture and economics students, as well as to industry people.

ACKNOWLEDGEMENTS

Several students and colleagues contributed to the development of this book. In particular I would like to thank Claire Armstrong, Harald Bergland, Eivind H. Brækkan, Arne Eide, Knut Heen, Bjørn Hersoug, Nguyen Ngoc Duy, Vina Ram-Bidesi, Malcom Jobling, Atle Lillehaug, Ragnar L. Olsen, Svein Ottar Olsen, Thi Khanh Ngoc Quach, Siv Reithe, Anders Skonhoft, Thanh Thuy Pham, Suthamathy Nadarajah, Thi Thanh Ngan Le, Tore Seternes, and Sverre B. Thyholdt, for comments and suggestions, Liv Larssen for typing and technical assistance, Frøydis Strand for production of several of the figures in the fisheries part, and the OECD for permission to use some of their material.

PART I INTRODUCTION

1 INTRODUCTION

The global production of wild fish, including mollusc and crustacean, increased steadily over the first four-five decades after the Second World War, but then came to a halt in the mid-1990s, at almost 90 million tons (Figure 1.1). After that, the catch stagnated and even declined a little since the turn of the century. On the other hand, aquaculture production grew faster than wild fish harvest and continue to do so also after the turn of the century. Aquaculture is man's controlled raising of fish in fenced facilities in sea, freshwater or on artificial ponds on land. Some places aquaculture has taken place for thousands of years, as in China and Egypt. Other places this is a rather new industry, such as salmon production in Chile and Norway. Fishing has taken place as long as man has populated the earth, but fisheries data from pre-historic time is of course lacking. Behind the global total catch figures in Figure 1.1, there is a huge number of fisheries, of which some have existed for centuries and done well decade after decade in modern time, whereas others have risen and declined. What are the causes and effects of the negative development of some and the successful development of others? Upon studying this book you should be well qualified to analyse and understand the development of specific fisheries and to indicate and advice on what remedies could be applied to improve economic and biological performance. Traditionally, the main problem in fisheries was that no one controlled the key resource, fish in the water. In aquaculture, the farmer in principle controls his own fish, but this may be negatively affected by diseases and other externalities from neighbouring farms. In addition, there may be negative effects from aquaculture to the wild fish stocks and other activities in the coastal areas.

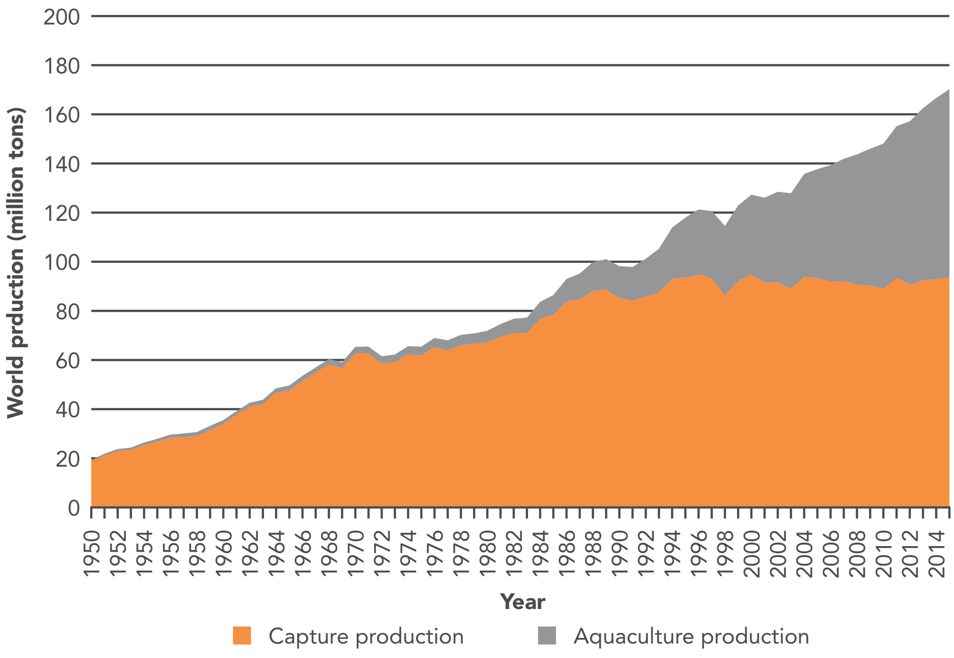


Figure 1.1. World capture fisheries and aquaculture production, 1950–2015, excluding plants. Sources: FAO, 2016; FishStat, FAO, 2017; Nadarajah. S., UiT – The Arctic University of Tromsø, personal communication.

Aquatic food production has gradually shifted from mainly catch of wild fish to more and more cultured products. In 2014 the aquaculture production for the first time overtook that of wild fish for human consumption (FAO, 2016). In addition to products for human consumption, more than 20 million tons of aquatic products are annually allocated for non-food uses, such as reduction to fish oil and meal (Table 1.1). As will be discussed further in part III of this book, fish oil and meal are largely used as input in the aquaculture industry.

The global supply of fish for human consumption has outpaced that of population growth in the past five decades. World per capita apparent fish consumption increased from 9.9 kg in the 1960s, to 14.4 kg in the 1990s and to 19.3 kg in 2013. Preliminary estimates for 2014 and 2015 points to further growth beyond 20.0 kg (FAO, 2016).

The capture fisheries included in Figure 1.1 and Table 1.1 are based on conventional, partly well known stocks of fish, molluscs and crustacean. However, recent research indicates that there still are huge quantities of underutilized non-conventional species of fish in the oceans, but these may be costly to exploit (Box 1.1).

TABLE 1

WORLD FISHERIES AND AQUACULTURE PRODUCTION AND UTILIZATION

	2009	2010	2011	2012	2013	2014
	(Million tonnes)					
PRODUCTION						
Capture						
Inland	10.5	11.3	11.1	11.6	11.7	11.9
Marine	79.7	77.9	82.6	79.7	81.0	81.5
Total capture	**90.2**	**89.1**	**93.7**	**91.3**	**92.7**	**93.4**
Aquaculture						
Inland	34.3	36.9	38.6	42.0	44.8	47.1
Marine	21.4	22.1	23.2	24.4	25.5	26.7
Total aquaculture	55.7	59.0	61.8	66.5	70.3	73.8
TOTAL	**145.9**	**148.1**	**155.5**	**157.8**	**162.9**	**167.2**
UTILIZATION[1]						
Human consumption	123.8	128.1	130.8	136.9	141.5	146.3
Non-food uses	22.0	20.0	24.7	20.9	21.4	20.9
Population *(billions)*	6.8	6.9	7.0	7.1	7.2	7.3
Par capita food fish supply *(kg)*	18.1	18.5	18.6	19.3	19.7	20.1

Note: Excluding aquatic plants. Totals may not match due to rounding.
[1] Data in this section for 2014 are provisional estimates.

Table 1.1 World fisheries and aquaculture production and utilization, 2009–2014, excluding aquatic plants. Totals may not match due to rounding.
Source: FAO, 2016

Box 1.1 Unfished mesopelagic fish

The current total catches of fish from the ocean amount to about 90 million tons, mainly from well researched fish stocks exploited by man for decades and centuries. However, gradually researchers have found that there are huge quantities of unfished biomasses in the world's oceans. These are the mesopelagic fish species living mainly at sea depths from 200 to 1,000 m. The fish is small, from one to 10–15 cm long and difficult and costly to catch. Mesopelagic fishes likely dominate the world total fish biomass. Recent acoustic observations and modelling show that such biomasses could be as much as 10 billion tons, which is about one hundred times the annual catch of fish. There is a close relationship between the open ocean fish biomasses and primary production of phytoplankton. Man has typically utilized species that are "easy" to catch and has a relatively high market price. This changes across time. Gradually fishing communities and researchers have learned about the commercial and scientific values of such species. The uncertainty about size and distribution of mesopelagic fishes is related to "difficult" to catch and their relative low market values.

(Source: mainly, Irigoien et al., 2014).

As long as people have been living on the earth, they have utilised fish and other renewable marine resources for food, clothes and other necessities. The species caught have varied across regions and time. For example, the Nordic countries have a several thousand-year history of utilisation of living marine resources. Fish species like cod, herring and salmon, as well as several species of seals and whales, have always been important elements in the diet of coastal people and as goods for trade. Historically, local people have had free access to these resources in the sense that no authority above the fishing village or tribal level decided how fishing could take place and the intensity of these activities. Natural short run and long run fluctuations in the size of fish stocks, fish migration, species composition and weather and climate, as well as seasonal variations in the availability of different species, represented the main challenge for the fishers. However, in particular during the twentieth century, several fisheries around the world have experienced more and more restrictions on the freedom of individual fishers to establish and conduct their business. In addition, technological change and the transformation of local supply fisheries to fisheries based on national and global markets have had an immense effect on the way fishers perform their profession.

The objective of these materials is to give a thorough introduction to and review of the theory of fisheries economics and management, illustrated by actual and stylised examples, such that the student may understand better why it could be beneficial for society at large to organise people's access to fishing, and how this may be done. Correspondingly, for aquaculture, there is a need to understand both the economics of farm operation at the micro level and aquaculture industry management, considering the externalities within the aquaculture industry and between this industry and wild fish fisheries as well as other economic activities in the coastal areas. Hopefully, this will contribute to the long-term improvement of fisheries and aquaculture management and the economic performance at both firm and industry level.

In economics, we study how human beings utilise scarce resources for the production and distribution of goods and services that have alternative uses. Scarce resources include labour, capital and natural resources. The relative emphasis on each of these resources varies across the sub-fields of economics. Historically the main emphases seem to have changed according to the perception of economists, and people in general, of which resource is the most scarce. In particular, over the last couple of decades environmental and resource economics have gained more and more ground within economic discourse and theory. This has probably been affected by the increase in industrial production, transport and population growth, and the implications of this for local communities and countries all over the world. Some global problems, such as climate change, may be the result of millions of decisions at the household, business and national level. For each of the economic agents pursuing their own private interests their emission of CO_2 as individuals might seem insignificant, but the total is huge and is expected to have serious long-term effects. Another example is biological and economic overfishing. Each fisher's catch might seem insignificant compared with the wide ocean and the size of the ecosystem. However, the total catches of many fish stocks around the world have contributed to biological and economic overfishing. This has at some points in time been the case, for example, for cod in Canadian, Icelandic and Norwegian waters, despite the relatively small catch of each fisher and vessel.

In this text, fisheries economic theory is partly used as a synonym for bioeconomic theory and partly for something wider, including the application of microeconomic theory to fishing industry issues. A distinctive feature of bioeconomic theory is that it aims at analysing and modelling the main interactions between fishers (economic agents) and fishstocks (resources that might sustain harvest), as well as studying how such interactions are affected by the managers (principals of the society). However, we admit that the analysis is limited to major economic and biological issues, excluding most post-harvesting issues, as well as social and legal issues. Some basic elements from biological modelling will be used, but we do not intend to go into any detail of biological modelling and analyses. There are several similarities between the methods used by economists and biologists. Within both disciplines, core elements are theories, models and statistical methods to test hypotheses and give predictions. Predicting economic growth and the growth of fish stocks is not that different from a methodological point of view.

The economic world is extremely complex and difficult to grasp, not just for lay people, but also for trained economists. Even within smaller economies, such as Norway, Namibia and New Zealand, not to mention major economies like China, the European Union, Japan and the United States of America, millions of transactions between firms, and between firms and consumers, are taking place every day. To gain an overview of the functioning of these economies it would not be sufficient to start collecting data and other empirical information from these markets. We also need theories and models to explain connections between important economic variables. From consumer theory we recognise concepts like budget constraint, utility and individual demand, and from the theory of the firm, or production theory, the concepts of marginal cost, average cost and supply curve are well known. Market theory integrates elements from the theories of consumers and firms and concepts such as total demand, market price and equilibrium are well known. Based on theories, the functioning of complex markets may be described in a sufficiently simple way to give students and other interested parties an understanding of how markets work, and researchers may derive hypotheses to be tested against economic data. This does not necessarily mean that theory has to come before empirical investigation. Sometimes empirical data may give the researcher ideas for further investigation of interesting economic relationships and create the foundation for developing theories and models.

A theory or a model is not necessarily better the more detailed and complex it is. More important is that it includes, in a simple way, those economic variables of most importance for the issues at stake, and that it contributes to our knowledge of the functioning of the economy. Regarding the application of economic theory, a model that simplifies and summarises the theory in a coherent way is often useful. We may say, there is nothing as practical as an excellent theory, with the exception of an excellent model. Fisheries economic theory is in its most condensed form applied welfare theory, with elements from consumer, production and market theory. Fisheries economic models have something in common with macro economic models with the focus on aggregated economic variables. In fisheries economics the focus is often on the aggregated effects of all fishers' actions, to allow comparison of, for instance, the total catch of all fishers and the natural growth of the fish stock(s). For information about actual fisheries, aquaculture, management and trade, see sources described in Box 1.2.

Markets and ecosystems are often fluctuating and the development of key variables such as prices of fish, catches and fish stocks is uncertain. Risk and uncertainty are, however, not explicitly included in the analyses presented in this book. Focus is on deterministic theory to keep the discussion as simple as possible.[1]

Fisheries economic theory includes positive as well as normative elements: positive since it may explain why some fish stocks are over-fished, others under-utilised or not used commercially at all. On the other hand, like parts of welfare theory, fisheries economic theory is also normative since it may give guidance as to how intensively fish resources should be used and how the fishing industry could be managed. This text includes both positive and normative theories and models.[2]

Box 1.2 Some useful web sources

FAO – Food and Agriculture Organization of the United Nations has an excellent web page http://www.fao.org/fishery/en with reports and data for the aquaculture and fisheries sectors, including statistical databases that are publicly accessible. The data is provided by FAO member countries. "The reliability of the analysis based on the data, and the quality of the advice to which it gives rise, depends on the reliability and quality of the data itself. To this end the FAO seeks to continue supporting and strengthening national capacity in the collecting, analysis and use of accurate, reliable and timely data. In this respect the FAO has a unique role in supporting the management and development of the aquaculture and fishery sectors."

Information on species and group of species used globally in aquaculture and fisheries can be found at http://www.fao.org/fishery/species/search/en. There are 548 Aquatic species fact sheets. For example, for three fact sheets I found 25 species of salmon, 55 species of cod and 4 species of carp (2016 12 08) with description of biological and ecological characteristics as well as industry use and further references. We learn about fish production in both capture fisheries and aquaculture – for cod the capture is much larger than in aquaculture whereas it is the opposite for carp and salmon.

FAO's subdivision Globefish has reports and statistics on global and regional fish trade – see http://www.fao.org/in-action/globefish/en/.

ASFA Aquatic Sciences and Fisheries Abstracts (ASFA) http://www.fao.org/fishery/asfa/en is an FAO headed abstracting and indexing service covering the world's literature on the science, technology, management, and conservation of marine, brackish water, and freshwater resources and environments, including their socio-economic and legal aspects.

Sources: FAO

FishBase http://www.fishbase.org/search.php is a global species database of fish (specifically finfish). It is the largest and most extensively accessed online database on adult finfish on the web. Over time it has evolved into a dynamic tool that is widely cited in scholarly publications. FishBase provides comprehensive species data, including information on taxonomy, geographical distribution, biometrics and morphology, behavior and habitats, ecology and population dynamics as well as reproductive, metabolic and genetic data. As of December 2016, FishBase included descriptions of 33,400 species and subspecies, 318,900 common names in almost 300 languages, 57,800 pictures and references to more than 50,000 works in the scientific literature. The site has about 700,000 unique visitors per month. Sources: Wikipedia and FishBase

OECD The organization for economic cooperation and development http://www.oecd.org/tad/fisheries/ has a fisheries section with a web site with data and reports on fisheries in particular in member countries, i.e. mainly industrialized countries. Annual statistics from member countries is published.

The Sea Around Us http://www.seaaroundus.org/ is a research initiative at The University of British Columbia, Canada that assesses the impact of fisheries on the marine ecosystems of the world, with analyses and reports on solutions to the problems.

Exercise 1.1

At internet, access the FAO at http://www.fao.org/fishery/en and http://www.fao.org/fi/website/MultiQueryAction.do? and find

1) What is the capture and aquaculture production of your own country (use FishStat or Country Profile)
2) What information on your country does the Fishery and Aquaculture Country Profiles fact sheet contain?

PART II FISHERIES

2 POPULATION DYNAMICS AND FISHING

This chapter shows the basic features of fish stock dynamics and how the stock is affected by fishing. The sustainable yield curve, yield as a function of fishing effort, is derived. This curve is an important bridge between the work of biologists and economists, and it will be used extensively throughout these materials.

2.1 GROWTH OF FISH STOCKS

A fish species that lives and is able to reproduce itself within a given geographical area is called a stock or a population. In fisheries science and management literature, the term "stock" is most common, whereas in the ecology literature "population" is generally preferred. Some authors use stock as a synonym for an exploited population, but in this text the term stock will be used for any population, whether exploited or not. Ecologically speaking a population is "a group with unimpeded gene flow". An example of the relationship between species and stocks is the North Atlantic species cod (*Gadus morhua*) which consists of several stocks, including the Canadian-Newfoundlandic, the Icelandic and the Arcto-Norwegian cod. In principle, stocks are self-contained entities, even though there might be some migrational exchange between them. Each stock has its own particular characteristics that may be genetic, a result of differing environments, or usually a mixture of both.[3]

Fish stock change depends on recruitment, natural mortality, individual growth and harvesting. This may be summarised as follows:

Stock change = Recruitment + Individual growth – Natural mortality – Harvest
= Natural growth – Harvest

Note that the stock change can be positive or negative if recruitment and individual growth together is greater or smaller, respectively, than natural mortality and harvest. Empirical research and theoretical reasoning have concluded that natural growth of fish stocks may be illustrated as bell-shaped growth curves as shown in figure 2.1. Growth curves could also be called yield curves since the natural growth of fish stocks might be harvested. For most fish species, lower stock levels mean relative higher recruitment and individual growth, whereas higher stock levels imply relative lower recruitment, lower individual growth and/or higher natural mortality due to density-dependent biological processes. Thus, the sum of growth-augmenting and growth-impeding factors is a bell-shaped growth curve with the highest growth at an intermediate stock level. The maximum natural growth is at stock level X_{MSY} in figure 2.1. If the natural growth of the stock is harvested, the maximum harvest is achieved for stock level X_{MSY} and this harvest is called the maximum sustainable yield (MSY). MSY could be, for example, 200 000 tonnes per year for a cod stock. In each case shown in figure 2.1 a stable equilibrium of the unharvested stock exists at level K, and this level is usually called the environmental carrying capacity of the stock.

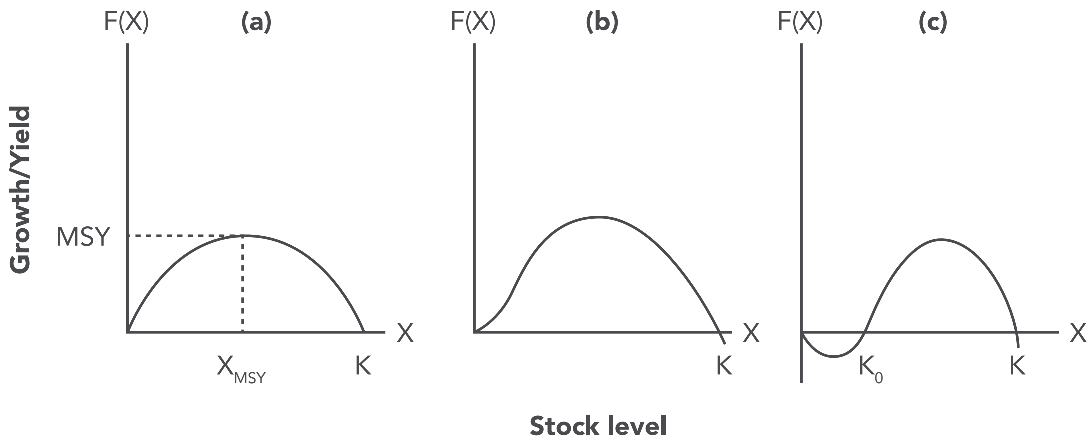


Figure 2.1 Growth curves with (a) compensation, (b) depensation, and (c) critical depensation.

For growth curve (a) in figure 2.1 the relative natural rate of growth *F(X)/X* increases when the stock level decreases, and we call this effect pure compensation. At low stock levels, some stocks have relative growth rates that decrease with reduced stock level. The growth of such stocks is said to be depensatory, and two growth curves with depensation are shown in panels (b) and (c) in figure 2.1. Growth curve (c) has a critical stock level K_0 which implies extinction if the stock should be depleted below this level for any reason. Depensation may be observed for some prey stocks, for example, herring, but not exclusively prey stocks. This feature may be the effect of a predator, for instance, seals, that continue to consume its prey even when the prey stock declines. Thus, in such a case the prey stock will demonstrate depensatoric growth. In case the predator is in strong need and has the ability to locate and consume the last school of prey, the prey stock is vulnerable to critical depensation and extinction if fished too hard.

For a thorough discussion of bioeconomic fishery models we shall need some simple mathematical tools. The following symbols will be used, where *t* indicates point in time:

$X(t)$ = Stock level (weight of the stock, for example in thousand tonnes)
$\dot{X}(t)$ = $dX(t)/dt$ = Change in stock per unit of time
$F(X)$ = Natural growth function.

Unless necessary for the understanding, the symbol for time, *t*, will be omitted in the text and equations.

For the natural growth function $dX/dt = F(X)$ the following characteristics are valid:

$$F'(X) = \frac{dF(X)}{dX} \gtrless 0 \quad \text{for} \quad X \lesseqgtr X_{MSY}. \tag{2.1}$$

A closer look at figure 2.1 reveals that the growth curves in panels (a) and (b) fulfil the requirements of growth function (2.1). However, this is not the case for very low stock levels in panel (c). Natural growth, expressed as in figure 2.1 and equation (2.1), is the limit to fishers' harvest. To produce a harvest, fishers need man-made tools and fishing effort, in addition to nature's tool, the fish stock. Without both, there will be no harvest.

Note that the growth curve in Figure 2.1 panel (a) is based on the natural growth function $F(X) = rX(1 - X/K)$ which we shall return to several times. In this function *K* is the carrying capacity of the habitat of this fish stock. Thus *K* is the maximum stock level, to be observed only before harvesting takes place. Further, *r* is the maximum growth rate, *F(X)/X*, to be observed only when *X* is close to zero.

Box 2.1 The Zarephath widow's pot

The importance of the supply of natural resources for people's survival and welfare have been described and discussed in both the secular and religious literature down the ages. The Bible, for example, mentions in several places water resources and their significance for people living in the area that today is called the Middle East. Issues related to the production of food from land and sea are also common themes in the Bible. The story of the Zarephath widow's pot is a case of renewable resource use. In fact, it was not just one pot in this story, but two – a jar and a cruse.

In 1Kings 17, the Bible tells how the prophet Elijah had been living from water of the stream Cherith, east of Jordan, and of bread and meat that the ravens brought him in the mornings and evenings. However, after a while the stream dried up because of lack of rain. Then God told Elijah to go to the town of Zarephath to stay with a poor and hungry widow. He came upon her at the gate of the city and she willingly shared her very last resources with him, using her final meal and oil to make a cake to be shared between Elijah, her son and herself.

And Eli'jah said to her, "Fear not; go and do as you have said; but first make me a little cake of it and bring it to me, and afterward make for yourself and your son. For thus says the LORD the God of Israel, 'The jar of meal shall not be spent, and the cruse of oil shall not fail, until the day that the LORD sends rain upon the earth.'" And she went and did as Eli'jah said; and she, and he, and her household ate for many days. The jar of meal was not spent, neither did the cruse of oil fail, according to the word of the LORD which he spoke by Eli'jah.
1 Kings 17, 13–16.

As the pots of the widow sustained her use of meal and oil, so the fish in the sea might sustain mankind's harvest. As long as harvesters use the resource within its production possibilities, the fish stock will give a lasting yield. However, it might go wrong if too many take too much from the same pot. A necessary, but not sufficient condition to avoid over-fishing is ecological and economic knowledge – that is to say, knowledge about interactions between man and nature.

Epilogue. Supply and sharing of resources are hardly as easy as in this story. Could it be that future "water wars" would be much harder, with more severe consequences for the people involved than some of the fish wars we have seen in recent decades? The Middle East area of Elijah and the widow in this story might be a candidate area for such wars. However, with co-operation and proper management conflicts may be avoided or reduced, for water as well as for fish resources.

2.2 EFFORT AND PRODUCTION

A fish harvesting firm or a fisher uses several inputs, or factors, to catch fish and to land it round, gutted or processed. Inputs used include fuel, bait, gear and labour. In this respect a harvesting firm is not much different from any other firm – a set of inputs is used to produce an output. However, the direct contribution from the natural resource, the fish stock, constitutes a significant difference compared with a manufacturing firm that can use as much as it wants of all the required inputs. A fisher can vary the amount of inputs, but not the size of the stock.

In actual fishing we usually find that for a given set of inputs the amount of output for the fishing firm varies with the stock level and the availability of the fish. Fish migration for spawning and feeding makes most stocks in certain areas more available for the fishers at some times of the year than in others. Such seasonal variations in the distribution of fish stocks and year classes are the basis for many seasonal fisheries around the world. However, to start with, we shall simplify the analysis by disregarding seasonal variations and assume that the fish stock is homogeneously distributed across area and time. The focus is on the size of the stock and the importance of this for the catch.

For analytical and practical purposes it is useful to let fishers encounter the stock with what is called fishing effort, or just effort. Examples of effort are hours of trawling, number of gillnets and number of long-line hooks[4]. Effort is produced by optimal use of inputs and is expressed in the production function

$$E = \Psi(v_1, \ldots, v_n), \qquad (2.2)$$

where E is effort and v_i is factor i. In one way, this is a regular production function recognisable from the theory of the firm. However, the great difference is that E is not a final product to be sold, like the products of most firms, but an intermediate good produced to encounter the fish stock.

Catch, the product of fish harvesting firms, is a function of effort and stock and this can be expressed in the harvest function

$$H = f(E, X). \tag{2.3}$$

Harvest function (2.3) is a short-run production function in the sense that it is valid for a given stock level at any point in time, without any feedback from effort to stock. Figure 2.2 gives an example of how catch varies with effort for two stock levels; H: high and L: low. Note that the catch is non-increasing in effort – that is, more effort implies higher catch, but not necessarily proportional to the increase in effort.

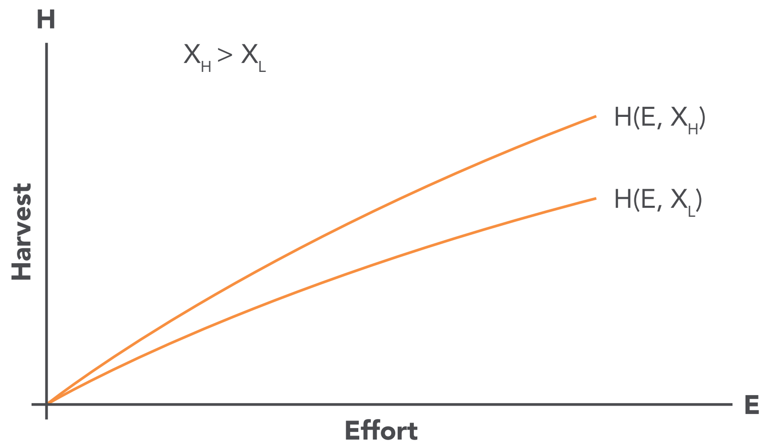


Figure 2.2. Short-run variations in harvest as a function of effort.

If effort is measured, for example, in trawl hours, catch could be measured in kg or tonnes. Effort and catch should both be related to the same unit of time, which could be a day or a week.

Thus, there is a dichotomy in the analysis of fish production that is not found in the traditional theory of the firm. This way of analysing fisheries has the advantage that it treats the inputs controlled by the firm, such as fuel, bait and gear, differently from the major input, fish stocks. The latter is a necessary factor of production affected by the actions of numerous fishers (see the next section), but not controlled by any of them.

2.3 YIELD AND STOCK EFFECTS OF FISHING

Fish stock levels are affected by fishing if the total effort is sufficiently high over some period of time. How much depends on the growth potential of the stock and the total harvest. Change in the stock is expressed by the growth equation

$$\dot{X} = F(X) - H. \tag{2.4}$$

From this equation follows

$$\dot{X} \gtreqless 0 \quad \text{if} \quad H \lesseqgtr (X). \tag{2.5}$$

To ensure positive growth of the stock, the harvest must be lower than the natural growth. Biological equilibrium is by definition achieved when X = 0, and in this case equations (2.3) and (2.4) give

$$f(E, X) = F(X). \tag{2.6}$$

Since this is one equation with two variables, X and E, the stock is implicitly given as a function of effort E. This means that at equilibrium the stock level is a function of effort, and from equation (2.3) it now follows that the equilibrium harvest is also a function of effort. This equilibrium harvest is often called sustainable yield since it can be sustained by the stock for a given level of effort.

We have seen that, knowing the growth function $F(X)$ and the short-run harvest function (2.3), the sustainable yield may be derived from equation (2.6). This can also be done graphically as shown in figure 2.3. To simplify the analysis we now assume that the short-run harvest function is linear in effort and stock level:

$$H = qEX. \tag{2.7}$$

Equation (2.7) is called the Schaefer harvest function (Schaefer, 1957). The parameter q is a constant called the availability parameter. This parameter expresses how effective the effort is in relation to the stock level. If effort is measured in, for example, gill net days, q expresses the ratio between catch per gill net day, H/E, and stock level, X. Thus, the value of q is directly linked to the scaling of E. In some fisheries the combined harvest technology and fish behaviour is such that catch per unit of effort, H/E, is nearly independent of the stock size (see Bjørndal, 1987). In other fisheries catch per unit effort increases with the stock level, but not proportionally as in the Schaefer function (see Eide et al., 2003).

Panel (a) of figure 2.3 shows short-run harvest as straight lines for five different effort levels. For the smallest effort E_1 the harvest curve crosses the growth curve for stock level X_1 and harvest H_1. Thus, a small effort – over a sufficiently long time to let the stock reach equilibrium – gives a high stock level and a relatively small catch. A somewhat higher effort level E_2 gives a lower stock level X_2 but a higher sustainable catch, H_2. However, an even higher effort like E_4 gives stock level X_4 that is significantly lower than X_2, even though the sustainable catch H_4 is equal to H_2. Similarly, E_5 gives a catch H_5 equal to E_1, even though the stock level X_5 is much smaller than X_1. In Figure 2.3 the highest possible harvest is reached for effort level E_3 and this harvest is called the maximum sustainable yield (MSY).

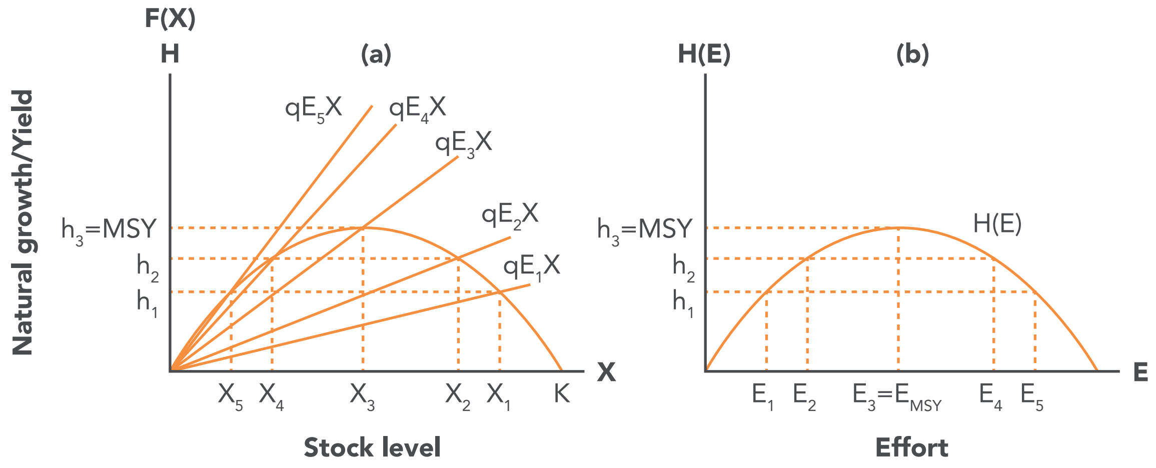


Figure 2.3. The sustainable yield curve shows harvest as a function of effort and is derived from the natural growth curve and the harvest curve.

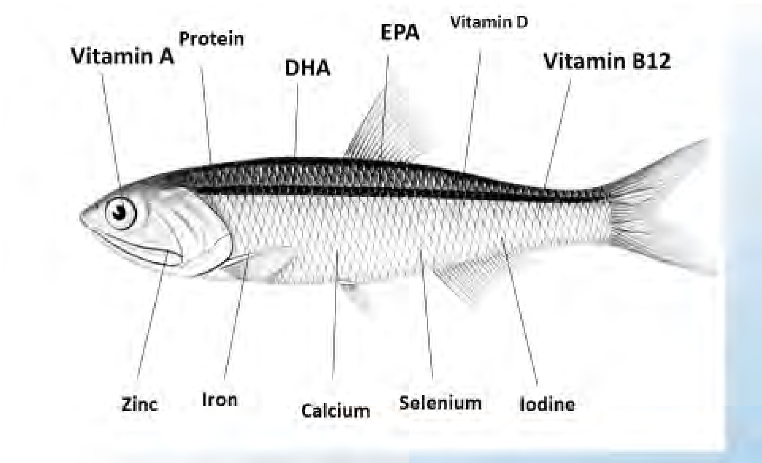
The natural-growth stock-level curve in panel (a) has been transformed into a sustainable-harvest effort curve in panel (b). The *H(E)* curve is also called the sustainable yield curve and it connects the long-run harvest potential to fishing effort. This harvest-effort curve has the same form as the growth curve in this case since the Schaefer short-run harvest function is linear in both effort and stock. It is important to note the difference between the short-run harvest function $H = f(E,X)$ in (2.3), depicted as straight lines in panel (a) of figure 2.3, and the sustainable yield curve *H(E)*, in panel (b). The former is valid for any combination of effort, *E*, and stock, *X*, at any time, whereas the latter is the long-run equilibrium harvest for given levels of effort. The sustainable yield curve is conditional on equilibrium harvest.

The main purpose of figure 2.3 is to derive the equilibrium harvest-effort curve shown in panel (b). Let us now use this to discuss what happens over time if fishing takes place outside equilibrium. Suppose fishers use effort E_1 to harvest a virgin stock at the carrying capacity level *K*. To start with, the harvest will be significantly greater than H_1 since the stock level *K* is bigger than X_1, and this implies that the stock level will decrease. When the stock decreases, the harvest will also decrease until it reaches such a level that, according to the short-run harvest curve designated qE_1X in panel (a) of figure 2.3, harvest equals the natural growth of the stock. The decrease in harvest will continue until stock level X_1 has been reached. At this point in time, harvest equals natural growth, and another equilibrium has been established. On the other hand, if fishers use effort E_1 to fish at a stock level lower than X_1 the stock will grow since natural growth is greater than harvest. The length of the transition period between, for example, the virgin stock level *K* and level X_1 depends on the biological production potential of the stock. Growth curves and sustainable yield curves, as shown in figure 2.3, may be used to compare different equilibria but cannot be used to tell how long a time the transition from one equilibrium to another will take.

Box 2.2 Fish as nutrition

"Fish is one of the most important sources of animal protein, accounting for about 17 percent at the global level, but exceeding 50 percent in many least-developed countries. It also provides other valuable nutrients such as the long-chain omega-3 fatty acids docosahexaenoic acid (DHA) and icosapentaenoic acid (EPA) – important for optimal neurodevelopment in children and for improving cardiovascular health. There is convincing evidence of beneficial health outcomes from fish consumption for reducing the risk of death from coronary heart disease and improving neurodevelopment in infants and young children, when the mother consumes fish before and during pregnancy. In addition to the health benefits of these macronutrients, fish also provides micronutrients not widely available from other sources in the diets of the poor. Greater attention is focusing on fisheries products as sources of vitamins and minerals. Small-sized fish species consumed whole, with heads and bones, can be an excellent source of many essential minerals such as iodine, selenium, zinc, iron, calcium, phosphorus, potassium, and vitamins such as A, D and B. The levels of these nutrients are also high in larger fish, but highest in the parts that are usually not eaten, such as heads, bones and viscera. Fish products are the main natural source of iodine and long-chain omega-3 fatty acids. Fatty fish can also be an important and unique source of vitamin D, which is essential for bone health. In areas lacking sun in winter and in cultures where the skin is not exposed to sunshine, vitamin D deficiency is increasingly acknowledged as a serious health problem."

Source: FAO, 2016, p. 152



So far in this chapter we have analysed the effects of fishing on a stock with growth compensation (see figure 2.1). However, if the growth process exhibits depensation or critical depensation, the sustainable yield curve proves to become very different from the case of compensation. This is demonstrated in figures 2.4 and 2.5. The former is for the case of depensation and the latter is for the case of critical depensation of growth. In figure 2.4 panel (a), E_D is the effort that makes the Schaefer harvest curve tangent to the growth curve at the zero stock level. Mathematically, E_D can be found from equation

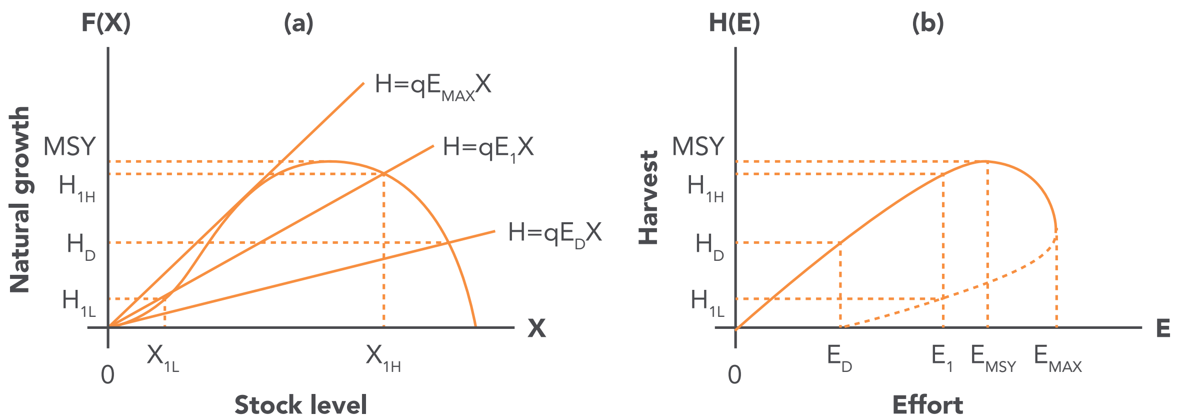


Figure 2.4. The natural growth curve and sustainable yield as a function of effort in the case of depensation.

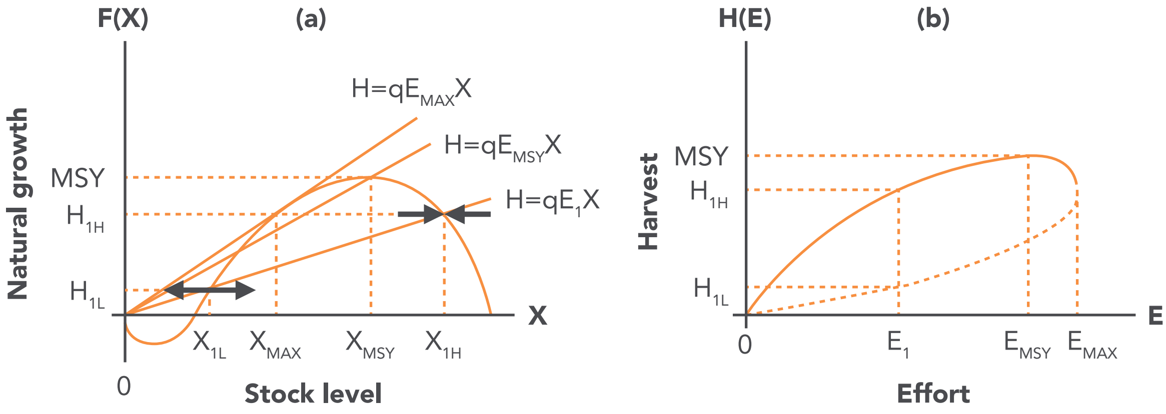


Figure 2.5. The natural growth curve and sustainable yield as a function of effort in the case of critical depensation.

$$qE_D = \lim_{X \to 0} F'(X)\,. \qquad (2.8)$$

The left-hand side (lhs) of this equation is the slope of the Schaefer harvest curve, and the right hand side (rhs) is the slope of the growth curve.

To ensure a sustainable harvest there is an upper limit on effort which cannot be exceeded, and this effort level is designated E_{MAX} in figures 2.4 and 2.5. If effort levels above E_{MAX} are maintained for a sufficiently long time the stock will be biologically over-fished and finally will become extinct. In case of extinction, panel (b) of figures 2.4 and 2.5 shows that the yield is zero for effort higher than E_{MAX}.

Figure 2.4 panel (b) shows that the harvest curve is double, with an upper and a lower branch for each value of effort between E_D and E_{MAX}. This is due to the existence of two intersection points between each of the linear harvest curves and the growth curve, as shown in panel (a). There is, however, a significant difference between the two branches of the yield curve. The upper part constitutes stable points of harvesting whereas the lower part constitutes unstable harvesting. An example will explain the stability problem. The harvest curve for effort E_1 intersects with the growth curve for two stock levels, the low one X_{1L} and the high one X_{1H} in panel (a) of figure 2.4. For stock levels lower than X_{1L} the harvest curve is above the growth curve and the natural growth is too small to compensate for the harvest. This implies that the stock will decrease from X_{1L} to zero if effort E_1 is maintained over a sufficiently long period of time, indicated in panel (a) by an arrow pointing to the left. Thus, X_{1L} is an unstable equilibrium for the stock harvested by effort E_1. This would also be the case for all other left-hand side intersections between the harvest curve and the growth curve for effort levels between E_D and E_{MAX}. On the other hand, if the stock level is just above X_{1L} natural growth is larger than harvest for effort E_1 and the stock will increase. An arrow pointing to the right indicates this. Therefore, in this case the stock will in the long run increase towards X_{1H}, which is a stable equilibrium. The lower part of the yield curve in figure 2.4 panel (b) is dashed to mark that this part represents unstable harvest. Figure 2.5 shows that, in case of growth with critical depensation, the harvest curve is double for all levels of E between zero and E_{MAX}. The lower part of the yield curve also represents unstable harvest in this case.

Exercise 2.1

Assume that the harvest function is $H(E,X)=qEX$, where q is the catchability coefficient and E is fishing effort. The catchability coefficient for a particular fishery is q=0.00067, and the stock level is X=3.0 million tonnes.

a) What is the catch per unit of effort (CPUE) in this case?
b) What could the unit of measurement of effort be if the fish stock is for example cod or hake?

Exercise 2.2

Assume that the function $F(X)=rX\left(1-\frac{X}{K}\right)$ describes the annual natural growth of a fish stock. X represents the stock biomass at the start of the year. K is the environmental carrying capacity in stock biomass terms and r is the intrinsic growth rate.

a) Show that the maximum sustainable yield (MSY) can be expressed by the two parameters r and K, so that $MSY=\frac{rK}{4}$.
b) Draw a picture of F(X) for r=0.4 and K=8.0 million tonnes.

Assume that the harvest function is $H(E,X)=qEX$, where q is the catchability coefficient and E is fishing effort measured in number of vessel year.

c) Show how the sustainable yield curve (the long-run catch function) H(E) can be found. Tip: find it graphically like in figure 2.3, or by use of $H(E,X)=F(X)$ where you eliminate X by using the harvest function.
d) Add to your picture of $F(X)$ the harvest function $H(E,X)=qEX$ for q=0.00067 and E equal to 100, 200, 400 and 500 vessel year. What is the sustainable yield for these levels of effort?

3 A BASIC BIOECONOMIC MODEL

In this chapter we shall use the sustainable yield curve derived in figure 2.3 to analyse economic and biological effects of fishing under open access and managed fisheries. The concept of resource rent is defined and discussed, and we demonstrate how important this concept is for the analysis of managed fisheries.

3.1 OPEN ACCESS BIOECONOMIC EQUILIBRIUM

Let us start by asking the following question: if fishers have open and free access to a fishery, is there an effort level that may give rise to an economic equilibrium in the fish harvesting industry in the sense that effort is stable over time? If the answer to this question is affirmative, then one might ask how economic factors like effort costs and fish prices affect effort and stock at equilibrium.

The gross revenue of a fishery, for example, per season or year, equals quantity harvested multiplied by the price of fish. The price of fish from a particular stock is hardly affected by quantity fished if the fish is sold in a competitive market with many sellers and buyers and in competition with similar types of fish from other stocks. In the following analysis we shall assume that the price of fish, *p*, is constant across time and quantity.

Based on the sustainable yield curve (see *H(E)* in figure 2.3) the total revenue of fishing can be represented as

$$TR(E) = p \cdot H(E). \tag{3.1}$$

The total revenue curve will simply have the same shape as the sustainable yield curve, scaled up or down depending on the actual price. It is important to notice that the total revenue function and curve are both in terms of effort. In micro-economics, however, revenue is usually related to output.

From the total revenue function in equation (3.1) we derive the average revenue and the marginal revenue functions. The average revenue per unit of effort is

$$AR(E) = TR(E) / E, \tag{3.2}$$

and the marginal revenue of sustainable fishing is

$$MR(E) = dTR(E) / dE. \tag{3.2'}$$

The distinction between the concepts of average and marginal revenue is very important in fisheries economics. Average revenue is the total revenue divided by total effort, whereas marginal revenue shows the change in total revenue as a result of a small change in effort. When we know the sustainable yield harvest, *H(E)* and the price of fish, *p*, we can also find *TR(E)*, *AR(E)* and *MR(E).* Figure 3.1 panel (a) shows the total revenue curve based on the sustainable yield curve in figure 2.3 and a

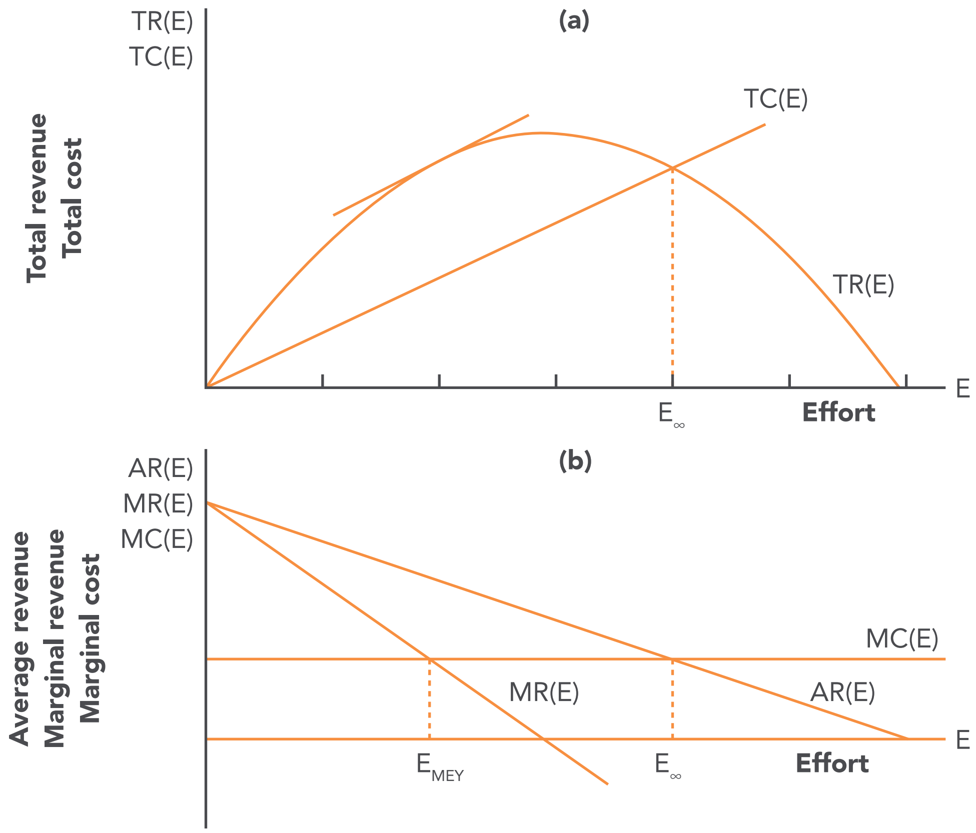


Figure 3.1. The maximum economic yield level of fishing effort is significantly lower than the open access level.

constant price of fish. The corresponding average revenue of effort *AR(E)* and marginal revenue of effort *MR(E)* curves are shown in panel (b). In this case the form of the *TR* curve is such that the *AR* and *MR* curves are almost straight lines. Whether they really are straight lines or curved is not of importance for this analysis. Note that for sufficiently high effort costs, or low price, the open access effort level in Figure 3.1 may be lower than the maximum sustainable yield effort, implying that the stock will be higher than its MSY level (also see Figure 2.3).

The total cost of a fishery depends on the costs and efficiency of each fishing vessel and its crew. However, at this stage we shall not go into a detailed discussion of the cost structure of the vessels. In the long run, actual effort expands by the addition of new vessels and the subtraction of old ones, as well as by varying the effort and efficiency of each vessel. To simplify the analysis, we shall assume that the total cost of a fishery can be expressed in a simple function of effort. In general, the connection between average cost of effort, *AC(E)*, and marginal cost of effort, *MC(E)*, on the one hand, and total cost, *TC(E)*, on the other is

$$AC(E) = TC(E)/E, \tag{3.3}$$

and

$$MC(E) = dTC(E)/dE, \quad dMC(E)/dE \geq 0. \tag{3.4}$$

If $dMC/dE > 0$ each additional unit of effort would be more costly than the previous ones, whereas $dMC/dE = 0$ means that effort can be added to the fishery at constant marginal costs. Increasing marginal cost means that the vessels are different from a cost and efficiency perspective. In this case we organise vessels along the effort axis with the most cost effective one to the left and the least cost effective ones towards the right (more on this in chapters 6.1 and 7.1). Constant marginal cost of effort implies that there is an infinitely elastic supply of effort – in other words, the supply curve is horizontal. In this case one could think of homogenous vessels that are added to the fishery at the same cost as the previous one. Homogenous vessels are, from a cost point of view, equally equipped and crewed and the marginal and the average cost of effort are the same for all vessels. Costs, including capital, labour and operating costs, per unit of effort could be denominated, for example, as $ per vessel year, vessel day, trawl hour or gill net day. In figure 3.1 panel (a) the total cost curve, *TC(E)*, is shown as an upward-sloping straight line. In other words, the cost function is linear in effort at a constant cost, *a*, per unit of effort.

$$TC(E) = aE. \tag{3.5}$$

Since effort in this analysis is homogenous from a cost point of view we shall also assume that vessels are homogenous from an efficiency point of view. This implies that they all catch the same amount of fish per unit of effort and that the average revenue is the same for all vessels. Under open access, vessels will enter the fishery if revenue per unit of effort is greater than cost per unit, and exit the fishery if cost per unit is higher than revenue. When average revenue of effort equals marginal cost of effort there will be an economic equilibrium with neither an incentive to leave nor an incentive to enter the fishery. Thus, we have now arrived at the following criterion for open access economic equilibrium in the fish harvesting industry

$$MC(E) = AR(E). \tag{3.6}$$

Recall that the revenue curves in figure 3.1 are based on biological equilibria ($\dot{X}= 0$) and that this is also the case for criterion (3.6). In other words, there are simultaneous biological and economic equilibria when (3.6) is fulfilled. This is called the open access bioeconomic equilibrium, or just bionomic equilibrium.

For homogenous vessels, as in the analysis of this chapter, effort and harvest are the same for all vessels. Thus, the catch efficiency is the same for all vessels. What factors determine this efficiency at bioeconomic equilibrium? Are biological or economic factors most important? Let us try to answer these questions by using the bioeconomic model analysed above. By taking the derivative of (3.5) with respect to E we have

$$MC(E) = a, \tag{3.7}$$

and from (3.1) and (3.2) follows

Box 3.1 Denomination of fishing variables

H and *E* in the harvest function (2.3) have to be related to the same time period, for example one day, month or year. The unit of measurement of effort, *E*, can be, for example, one hour of trawling in demersal trawl fisheries, one gill net day in coastal gill net fishing, or 100 hooks in long line fisheries. Using Δt as symbol for the unit of time, one hour of trawling as the unit of effort and metric tonne as the unit of harvest and stock, the denominations of the variables would be

E: Trawl hours/Δt
H: Tonnes/Δt
X: Tonnes

The unit of time used for measuring *TR* and *TC* has to be the same as for measuring *H* and *E*. The denomination of the cost per unit of effort, *a*, would be $ per trawl hour, $ per gill net day or $ per 100 fishing hooks, respectively, using the above examples. The denominations in $ terms will be

a: $/trawl hour
$TC = aE$: $/$\Delta$t
$TR = pH$: $/$\Delta$t

If one vessel produces *s* units of effort during Δt, *Z* vessels will produce the total effort

$$E = s\, Z\, \Delta t$$

If we know the total effort and the number of vessels, the average effort per vessel is found by dividing trawl hours with the number of vessels times the unit of time

$$s = E/Z\Delta t.$$

$$AR(E) = \frac{pH(E)}{E}. \tag{3.8}$$

Substituting for *MC(E)* from (3.7) and for *AR(E)* from (3.8) into (3.6) and re-arranging somewhat gives the following

$$\frac{H(E)}{E} = \frac{a}{p}. \tag{3.9}$$

The left-hand side of (3.9) is called catch per unit of effort (CPUE), and this is equal to the ratio of cost per unit of effort to price of fish. It may seem strange that only economic factors, and not biological, affect CPUE at the open access bioeconomic equilibrium. How is this possible? Firstly, note that *E* and *a* are closely related. If *E* is measured, for example, in trawl hours, *a* will be in $ per trawl hour, and if *E* is measured in trawler year, *a* will be in $ per trawler year. CPUE will be tonnes per trawl hour or tonnes per trawler year, correspondingly. At bionomic equilibrium, CPUE will be greater the greater cost of effort and the lower price of fish is. Biological conditions do not affect the productivity of fishing, according to (3.9). The reason for this is that the open access stock level is an endogenous variable determined together with the sustainable catch, effort and CPUE by the exogenous variables; effort cost and fish price (see also Ch. 5.2). The ratio of cost of effort-price of fish affects fishing and thereby the size of the stock and the CPUE; low effort cost and high fish price imply a low equilibrium stock level under open access harvesting.

In actual fisheries, prices, costs, efficiency and fish stocks fluctuate over time and economic and biological equilibria are only rarely observed. Nevertheless, the open access model has proved a useful point of reference in fisheries economics, just as the model of perfect competition is a useful reference model for understanding economics in general.

3.2 MAXIMISING RESOURCE RENT

Economic rent is, generally speaking, a payment to a factor of production in excess of what is necessary for its present employment. For example, if a fisher makes $20 000 in his present occupation as a participant in an open-access fishery and his second best alternative, as a builder, pays $18 000, the economic rent is $2000. If his neighbour is a less efficient fisher who makes only $18 000, which is just above his opportunity cost in the labour market, this fisher does not earn any rent. The kind of rent earned by the former fisher is called intra-marginal rent (more on this in Ch. 7.1), which is closely related to rent from land discussed by classical economists like Ricardo. In Ricardo's context, rent is payment for the use of land: "the uses of the original and indestructible powers of the soil" (Ricardo, 1821, p. 33).

In present day economies, firms in some industries have monopoly power, which is the ability to influence the market price of the goods or services they sell. If such a firm generates revenue exceeding all its opportunity costs, including normal profit, super-normal profit is generated. Normal profit is the necessary payment to attract and keep capital in an industry. This may vary since risk and uncertainty vary between industries. Super-normal profit in this context is also called monopoly rent. Monopoly rent is related to the downward-sloping demand curve for the goods produced by a firm, whereas the intra-marginal rent noted above is related to the upward-sloping marginal cost curve of an industry. In the latter case the intra-marginal producers are more efficient than the marginal one that just breaks even.

In fisheries, there is a possibility of generating another type of rent related to the common pool characteristics of fish as a natural resource. This rent, called resource rent, is the industry earnings in excess of all costs and normal profit, and this may exist independently of any monopoly or intra-marginal rent. We shall see this more clearly when there is a horizontal marginal cost curve (no intra-marginal rent) and a horizontal demand curve (no monopoly rent) at the industry level. Using the previous symbols, resource rent is defined, within the sustainable harvest model, by

$$\pi(E) = TR(E) - TC(E). \tag{3.10}$$

The resource rent equals the revenue in excess of all costs, and this will vary with fishing effort. Assuming that the objective of fisheries management is to maximise the resource rent, let us now derive the effort level that can realise this objective. Note that alternatively we could have used harvest, H, as the management instrument instead of effort, E. Whether we use harvest or effort is mainly a matter of convenience and tradition. For a given effort the corresponding equilibrium harvest follows from the sustainable yield curve derived in chapter 2. To find the optimal level of effort, we may think of a sole owner that has total control of the fishery, including the control of effort and exclusive right to use the resource; Gordon (1954) and Scott (1955) are early proponents of this approach. A necessary condition for maximisation of $\pi(E)$ in (3.10) is

$$d\pi(E)/dE = MR(E) - MC(E) = 0, \tag{3.11}$$

where $MR(E) = dTR(E)/dE$ is the marginal revenue of effort for sustainable fishing and $MC(E)$, the marginal cost of effort, is defined in (3.4). The second order condition for maximisation of $\pi (E)$ is

$$d^2\pi(E)/dE^2 = dMR(E)/dE - dMC(E)/dE < 0. \tag{3.12}$$

From the necessary condition (3.11) we derive the following condition for maximum resource rent

$$MC(E) = MR(E). \tag{3.13}$$

The optimality rule in (3.13) is a very important economic reference point for fisheries management. Note the difference between this rule and the open access rule in (3.6). In both cases the left-hand side is the same, the marginal cost of effort $MC(E)$, whereas the right-hand side differs. Under open access the effort expands and the stock decreases until the average revenue, $AR(E)$, is reduced and equals marginal cost of effort at the bionomic equilibrium. In order to maximise resource rent, effort has to be reduced to such a level that the marginal revenue $MR(E)$ equals marginal cost, as shown in (3.13).

Maximum resource rent is also called maximum economic yield, with the acronym *MEY*. Effort and stock level corresponding to maximum economic yield are therefore given the subscript *MEY* as shown above in figure 3.1. This figure shows that E_{MEY} is significantly lower than E_{MSY}. The reduction of effort compared with the open access effort level saves costs and/or enlarges fishery revenues. Figure 3.1 has been designed such that revenue is about the same under open-access and *MEY* fishing and this is also the case for quantity harvested since price per kg of fish, *p*, is constant – independent of quantity harvested. But how is it possible to harvest the same quantity of fish with two such different effort levels as under open access and *MEY* fishing? Recall that to harvest fish we need two major inputs, effort and stock, as expressed in the harvest function (2.3). To harvest a certain quantity of fish one may choose a large fishing effort and a small fish stock, or a small effort and a large stock. From an analytical point of view we compare two different equilibria without taking into account the time needed to change from one stock level to another. The sustainable yield curve (shown in figure 2.3) and the above analysis allows for comparison of different biological and economic equilibria, without paying regard to the time dimension (time and investment will be studied in Ch. 4). It is pretty obvious that to maximise resource rent within the above analysis it pays to use the small effort-large stock combination, instead of large effort-small stock.

Under the open access regime each fisher does not have an incentive to save fish in the sea to let it grow and to let it spawn new recruits for later periods of fishing. If fisher Mary wanted to pursue such goals it is very likely that Peter, Paul or another fisher, or all of them, would take such an opportunity to catch what Mary left. This leaves Mary without any other choice than to behave selfishly and maximise her own goal at any time. Thus, under open access the fish in the sea has zero opportunity cost for each fisher, resulting in the large-effort small-stock equilibrium.

Under *MEY* management the resource has a positive opportunity cost due to the spawning and growth capacity of fish that can be used for harvesting and to maintain a larger stock than the open access provides. A larger stock gives lower unit cost of harvest ($ per tonne) than a small stock. This cost saving effect of increased stock level, called stock effect, is utilised to generate resource rent under the MEY regime.

The analysis in this text is based on the assumption that effort, which combines inputs like vessel, gear, fuel, and labour, has an alternative value in the society's production. This is a reasonable assumption for the long-term adaptation analysed within a bioeconomic framework. It takes time for stocks to adjust to changes in effort and other exogenous factors. Factors of production used to produce vessels and gear could alternatively have been used for the production of other goods and services for consumption and investment.

When a society's resources and outputs are allocated in such a way that no feasible change can improve anyone's welfare without reducing the welfare of at least one other person, then a Pareto optimum exists (named after Vilfredo Pareto, Italian economist and mathematician, 1848–1923). A reallocation that makes one person better off without making anyone else worse off is called a Pareto improvement. From our analysis it should be clear that open access harvesting is not Pareto optimal. By reducing effort from E_∞ to E_{MEY}, as shown in figure 3.1, society saves on some factors of production that can be used in other sectors of the economy. This saving of resources should make it possible for the society to realise a Pareto improvement. Note that this criterion is rather strict, requiring that the improvement should take place "without making anyone else worse off". However, economic development often takes place with net gains for someone, but losses for others. Even if total gains are larger than total losses in monetary terms, such a change is not a Pareto improvement because of the losses for someone. The Kaldor-Hicks criterion says that if a change in the economy is such that the gainers could compensate the loosers and still be better off, this change is beneficial for the society as a whole (J.R. Hicks and N. Kaldor published their work in 1939 in the *Economic Journal*). Compensation is hypothetical and this criterion suggests that the change is preferable even if compensation does not actually take place.

3.3 EFFORT AND HARVEST TAXES

In the previous section we have seen that a fishery can provide an economic surplus, resource rent, if effort is reduced below the open access level. We also derived the effort level E_{MEY} that maximises resource rent. Using the sustainable yield curve, *H(E)* in figure 2.3, what the rent maximising harvest, H_{MEY}, is follows immediately. The analysis so far does not tell how the reduction in E could take place. In many countries regulation traditionally plays a key role in managing fishing capacity and effort. We may think of capacity in numbers and size of vessels whereas effort is related to use of vessels in fishing. Examples of management instruments for capacity and effort reductions include vessel and fisher licences, effort quotas, length and weight limits for hull and fitted vessels, as well as engine power limitations. Such regulations are called input regulations. Output regulations related to the harvest of fish are called quotas – be it total harvest quotas or harvest quotas per enterprise, vessel or fisher. In addition, input and output regulations may be combined with technical regulations, which include minimum mesh size of gear, minimum size of fish, and closed areas and seasons. Some of the regulatory instruments may be transformed into market instruments, such as tradeable licences and quotas (more on this in the next section).

Indirect management instruments include taxes, fees and subsidies. The latter, for example a fuel subsidy, would encourage an expansion of effort and can be disregarded as an instrument to reduce effort in the direction of E_{MEY}. In other parts of the economy corrective taxes are used to discourage the use of some goods and services, for example, motor vehicle fuel and tobacco, and to finance government budgets. Corrective taxes can in theory bring marginal private costs into alignment with marginal social costs. Such instruments are called Pigouvian taxes (after the British economist A.C. Pigou, 1877–1959). In principle, these could be used in fisheries, even though in practical fisheries policy they are hardly the regulatory means of primary choice among major fishing nations (see, for example, OECD, 1997). Nevertheless, studying the effects of Pigouvian taxes on fishing effort, as well as on resources, is an excellent point of departure for studies in fisheries management – and to gain a basic grasp on how economic instruments work. Therefore, let us have a closer look at the effects of taxes on effort and harvest.

We have seen in sections 3.1 and 3.2 that a renewable resource like fish is economically overexploited under an open access regime, provided the market price is high enough and the harvest cost low enough to make it a commercial resource. Another interpretation is that the bioeconomic model predicts that open access fisheries, in the long run, will not generate resource rent. Figure 3.1 shows that the average revenue per unit effort, *AR(E)*, is greater than the marginal cost of effort, *MC(E)* if total participation in the fishery, measured by E, is less than E_∞ The existence of a super-normal profit for the participants attracts new fishers with the result that total effort increases. This will take place as long as E is less than E_∞. On the other hand, if effort at the point of departure for our analysis is greater than E_∞ fishers will have higher costs than revenues and some of them will leave this fishery. Thus, E_∞ is the open access equilibrium level for effort as long as prices and costs are constant, and to this effort corresponds an open access equilibrium level of the fish stock.

In public discourse "the tragedy of the commons" seems to have several meanings, including that effort is higher than the maximum sustainable yield effort, effort is higher than the maximum economic yield effort, stock level is lower than the maximum sustainable yield stock and that sustainable yield is lower than maximum sustainable yield. It is, however, important to distinguish between "tragedies" related to biological concepts and to economic concepts. A fish stock that is economically over-fished, as is always the case at open access equilibrium, is not necessarily biologically over-fished. If fishing costs are high and/or fish price is low, open access does not necessarily attract enough effort to cause biological over-fishing. The equilibrium effort has to be higher than the maximum sustainable yield effort to cause biological over fishing, and this will not happen unless the effort cost is sufficiently low and/or the fish price is high enough.

Based on the analysis above it is now clear that the management board should aim at doing something with the prices, costs or institutions that fishermen face. For fishermen high fish prices may be good in the short run, but with bad institutions (open access) this may in the long run be a threat against fish stocks. Using Pigouvian taxes, the manager's task is to find the tax rate, on either effort or harvest, that adjusts effort to the maximum economic yield level E_{MEY}. This requires an extensive knowledge about the biological and economic characteristics of the fishery, expressed in the *H(E)*, *TR(E)* and *TC(E)* functions. However, any tax rate lower than the optimal one will move the fishery in the right direction, from E_{∞} towards E_{MEY}. Let us now assume that the manager has all the necessary information freely available so that we do not have to include information and management costs in the analysis. Panel (a) of figure 3.2 shows total revenues and costs, whereas panel (b) shows average and marginal figures.

The following symbols will be used:

t_E = tax per unit effort (for example, \$ per trawl hour or trawler year)
t_H = tax per unit harvest (for example, \$ per kg or tonne of fish landed).

With an effort tax the total cost for the fishers is

$$TC_P(E) = (a + t_E)E, \tag{3.14}$$

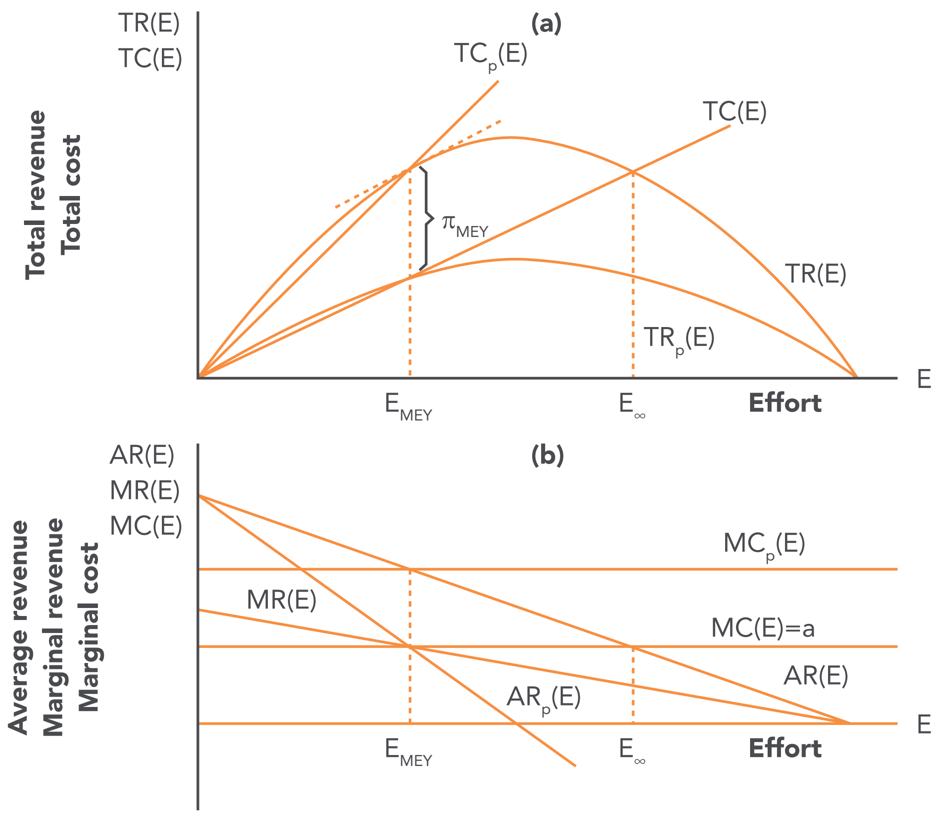


Figure 3.2 Use of corrective (Pigouvian) taxes on effort and harvest can equate social and private costs and social and private revenues.

where E and a are effort and cost per unit of effort, respectively. The use of subscript p for TC underlines that this is the total private cost of the fishers, including what they have to pay in effort taxes to the government. Note that for any value of E total private cost TC_p is greater than the total cost, TC, since fishers have to include the effort tax in their costs. The effect of an effort tax can be analysed equivalent to a shift in the cost per unit effort, thus increasing the slope of the total cost curve for the industry. This is shown in figure 3.2, where $TC(E)$ is the total cost curve exclusive of the effort tax and $TC_p(E)$ is the total cost curve including the tax. The effect of the effort tax is to augment total private costs to such a level that the TC_p curve intersects the total revenue curve for the maximum sustainable yield effort level E_{MEY}. This implies that the total revenue, $TR(E)$, is shared between the government, as the tax collector, and the fishing industry. The former receives the resource rent, π_{MEY}, and the fishers end up with the difference between the total revenue and the resource rent, $TR(E)$ minus π_{MEY}. Fishers in total receive $TR(E)$ for their catch, and out of this they pay a tax proportionate to their effort. What is left is just enough to cover the costs of the fishers. Recall that ordinary remuneration of capital and labour is included in the costs.

The total amount of resource rent depends on biological and economic characteristics of the fishery, related to the forms of the curves in figure 3.2. In general, we could say that low cost fisheries with high priced and/or easy to catch fish have the greatest potential for generating resource rent. On the other hand, high cost fisheries with low priced and/or hard to catch fish may even make it uneconomical to sustain a fishery on a commercial basis. Realising resource rent has a meaning only when a fishery generates, or is expected to generate, higher revenues than costs.

With a harvest tax the total private revenue of fishers equals

$$TR_P(E) = (p - t_H)H(E) \tag{3.15}$$

where p and H are the price of fish and of harvest, respectively. Note that TR now has the subscript p to underline that the total revenue in (3.15) is what the private industry receives net of taxes. The other part, equal to $t_h H(E)$, is the government's tax revenue. It is easy to see by re-arranging (3.15) that the total revenue of the fishery, $p_H(E)$, equals the sum of private and government revenues. Recall that the tax rate t_h is measured in $ per kg or per tonne – in other words we do not use a percentage tax in this analysis.

Figure 3.2 panel (b) shows in detail the effects of the two taxes discussed above. The MC, AR and MR curves are the before-tax fishery marginal cost, average revenue and marginal revenue, respectively. The open access bioeconomic equilibrium is at the effort level E_∞ where the fishery marginal cost curve intersects the average revenue curve. In this case with a horizontal MC curve the effort tax shifts this curve upward to MC_p, a distance equal to the size of the tax. If, for example, the fishery marginal cost is $100 per trawl hour and the effort tax t_E also equals $100 per trawl hour, the fishery marginal cost including the tax will be twice the pre-tax level. In figure 3.2 panel (b) this is illustrated with a MC_p curve at a level twice as high as the MC curve. The MC_p curve intersects the AR curve for an effort level that gives maximum economic yield, E_{MEY}. The industry now faces the effort cost including the tax and this will equal average revenue AR at equilibrium. For effort levels lower than E_{MEY} the AR curve is above the MC_P curve. This implies that additional effort will enter the fishery due to super-normal profit in the industry, and the stock will decline to reduce the average revenue along the downward sloping AR curve towards the E_{MEY} level. On the other hand, if effort is above the E_{MEY} level the effort cost including the tax is above the average revenue curve, imposing a loss on the participating vessels. This implies that some effort will have to leave the industry, resulting in lower catch, increased stock level and increased average revenue when moving from the right along the AR curve towards E_{MEY}. In case of an effort tax as the only management instrument fishers will face a higher cost of effort, but in all other respects their adaptation will be as under open access.

In case of a harvest tax, the average and the marginal revenue curves of the sustainable fishery are affected as shown in figure 3.2 panel (b). If the price of fish is $2.00 per kg and the harvest tax is \$1.00 per kg, the net price of fish received by the fishers will be \$1.00. Whether fishers receive \$2.00 per kg and are charged a tax of \$1.00 per kg, or they receive the net price of \$1.00 does not make any difference to their net revenues. In the latter case the \$1.00 harvest tax is levied on the buyers who collect the tax on behalf of the government. With this example the $AR_p(E)$ curve has a slope about half as steep as the $AR(E)$ curve in figure 3.2. This is due to the definition of average revenue; namely total revenue divided by effort. With a constant price of fish the numerator of the average revenue will change in proportion with the harvest tax for a given level of effort. The right-hand side end point of the average revenue curve on the effort axis will not be affected by the harvest tax; thus the intersection is at E_k for both the AR and the AR_p curve.

In figure 3.2 the level of the effort tax is such that the linear TC_p curve intersects the total revenue curve for E_{MEY}. This implies that the total tax revenue equals the resource rent:

$$\pi_{MEY} = t_E E_{MEY}. \qquad (3.16)$$

In the case of a harvest tax in figure 3.2 the level of this tax has been set such that the TR_p curve intersects the total cost curve for E_{MEY}. The resource rent in this case is exactly of the same amount as the tax revenue:

$$\pi_{MEY} = t_H H_{MEY}. \qquad (3.16)$$

By use of taxes on effort or harvest, the profit maximising behaviour of fishers results in lower effort than under open access, and those who stay in the industry earn a normal remuneration. Open access fisheries give, as we have seen, too many fishers in the industry, but resource taxes on effort or harvest could positively alter this. Thus, a tax on harvest contributes to decreasing the total revenue of the industry whereas a tax on effort contributes to increasing the industry costs. Resource taxes levied on effort or harvest would change the private cost or private revenue, respectively, to discourage participation in the fishery. The tax authority, traditionally the central government, collects the resource rent generated. This tax revenue may be used to reduce other taxes or to augment the government's expenditures. From a policy point of view resource rent can be re-distributed, for example, to fishing communities or regions, without any efficiency loss. The question of how the resource rent is spent or re-distributed should be seen independently of the problem of generating the rent. That is one of the strengths of this analysis. However, in actual commercial fisheries resource taxes have not been a common management instrument, like in other environmental and natural resource saving relations (for an overview of environmentally related taxes in industrialised countries, see OECD, 2001; OECD 2003; and The Environmental Taxes Database of OECD at http://www.oecd.org/). See Flaaten, 2010 on what may happen to fisheries dependent regions and countries if distributional issues are neglected.

Management does not come for free. There are costs of research and assessment of fish stocks and markets, as well as costs of obtaining information on costs and earnings of fishing vessels. In addition management and enforcement systems are necessary institutions which need economic funding. In some cases locally limited ecosystems may be governed more efficient and less costly by fishermen and other stakeholders themselves (see Ostrom, 1990, which is one of the major works that gained professor Elinor Ostrom the 2009 Nobel price in economics).

3.4 FISHING LICENCES AND QUOTAS

We have seen in the previous section how effort and harvest taxes could be used to reduce effort down to or towards the long run optimum, the rent maximising level. How much effort is reduced from the open-access level depends on the size of the tax, which in this case acts as a price instrument. In simple cases like this, with a single resource and no distinction between year classes, with one-dimensional effort (no substitution[5] between inputs), no management costs and no uncertainty, the manager may choose freely between indirect price instruments (taxes) and direct instruments, such as effort and harvest quotas. Price management (taxes) and quantity management (quotas) have equivalent effects on overall industry production and economic performance, therefore they are called dual instruments. However, to ensure that the expected results are lasting, the effort quotas and harvest quotas should be transferable. This means that there has to be a quota market to ensure that at any time the most cost-effective fishers do the fishing. In a successful MEY-managed fishery resource rent per unit effort would be Π_{MEY}/E_{MEY} and resource rent per unit harvest would be Π_{MEY}/H_{MEY} (recall figure 3.2). These two ratios indicate the equilibrium prices of effort and harvest quotas, respectively.

In actual fisheries the initial distribution of the fishing rights, such as vessel licences, effort quotas and harvest quotas are often heavily debated. There could be several reasons for this, but the main one has to do with the distribution of resource rent, which may be significant in well-managed fisheries. Even in a system with non-transferable harvest and effort quotas, significant resource rent may still be generated, in particular, if the initial quotas are given for free to those fishers that are most successful under the open access regime. The question is, however, whether these fishers also in the future will be the most efficient ones.

Let us now have a closer look at the effects of using licences and quotas as management instruments and compare the results to that of taxes. A vessel licence is a permission to register and use a vessel for commercial fishing. The licence may or may not specify limits to the vessel characteristics, for example, length (metres), weight (gross registered tonnes), hold volume (cubic metres) or engine power (horse power or kilowatt), and to the type of gear (for example, trawl, long-line or purse seine). A licence usually restricts the fishing capacity of the vessel; in general capacity is the amount of fish that can be produced per unit of time, for example, per year, with existing vessel, equipment and gear at a given stock level, provided the availability of variable factors of production is not restricted.[6] While capacity is related to the mere existence of the fishing vessel, effort is related to its use, measured for example, in hours, days or years. What to use as the unit of effort is mainly a question of convenience (see Box 3.1). In what follows we shall focus on effort and harvest quotas as management tools without discussing explicitly the use of licences. However, there is a close connection between the licence value and the quota value, depending on the amount of harvest quotas or effort quotas a licence holder is given or allowed to acquire.

Figure 3.3 is derived from figure 3.2 and shows effort along the horizontal axis and market price of effort along the vertical axis. Effort and its market price are both related to the same unit of measurement. For example, if effort is measured in trawl hours the effort quota price is in \$ per hour trawling, and if effort is measured in whole-year operated trawlers, the price is in \$ per trawler year. Resource rent per unit effort is the difference between the average revenue per unit effort, *AR(E)*, and the marginal cost of effort, *MC(E)* (see figure 3.2). In a perfect market, disregarding uncertainty, the effort quota price reflects the expected resource rent per unit effort and the harvest quota price reflects the expected resource rent per unit harvest. The licence price in figure 3.3 has its maximum for just one unit of effort, recalling that the highest average resource rent is gained if only one unit of effort participates in the fishery. At the other end of the effort price curve is the zero price for the open access case. The quota price is zero if the number of effort quotas equals the amount of effort that would establish itself under open access. In an open access fishery the market price of quotas is zero because no resource rent is generated. The total value of the quotas is, as usual, the product of price and quantity. In this case the maximum total value of the effort quotas, which is the product $m_{MEY}E_{MEY}$ shown in figure 3.3, is equal to the maximum resource rent, Π_{MEY}, shown in figure 3.2. Note that this analysis relates to long run equilibrium harvesting where the manager has adapted the number of effort quotas to maximise resource rent.

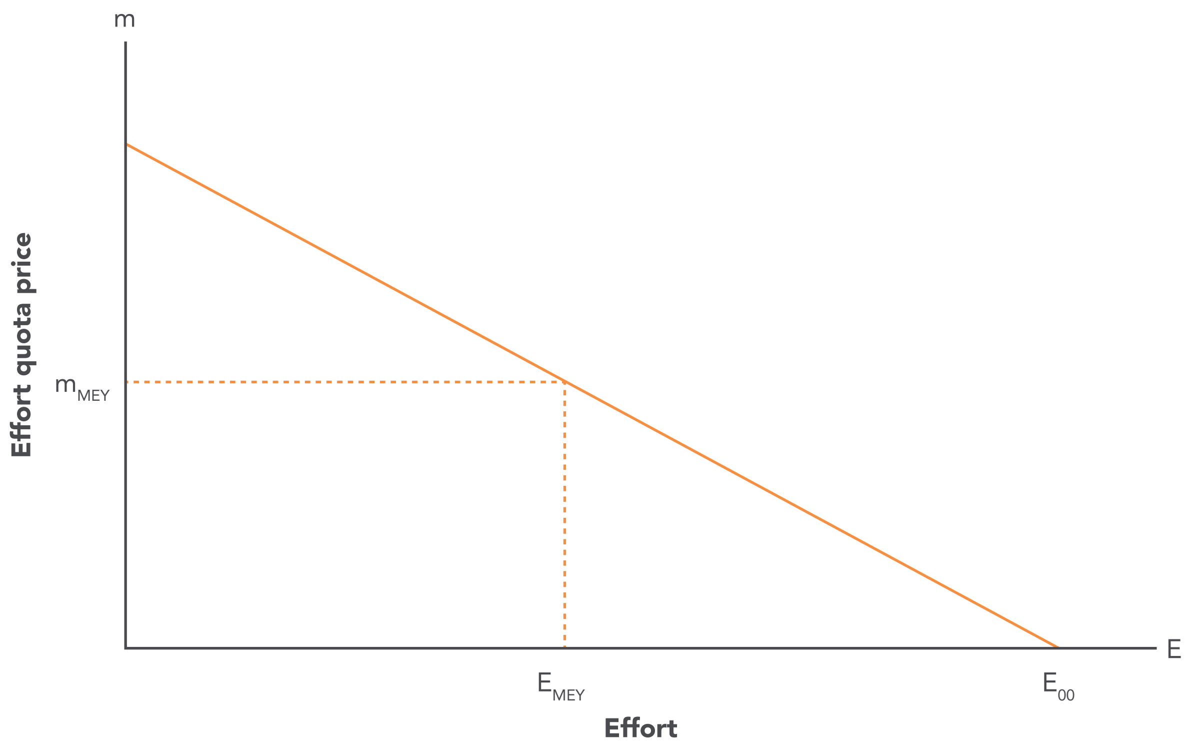


Figure 3.3. Effort quota price as a function of sustainable effort.

So far in this chapter we have studied some long-run aspects of fisheries, in particular the cases of open-access and MEY management, assuming that the supply of homogenous effort is plentiful at a constant marginal cost of effort, previously denoted *a*. However, from the theory of the firm we recall that increasing marginal cost is necessary to avoid corner solutions with "all" or "nothing" production. In fisheries economics the declining stock as a function of effort helps avoid corner solutions, as shown in figure 3.2.[7]

Let us now assume that in the short run there is increasing marginal cost of effort at the firm level (more on this in chapter 6). This means that if there is a market

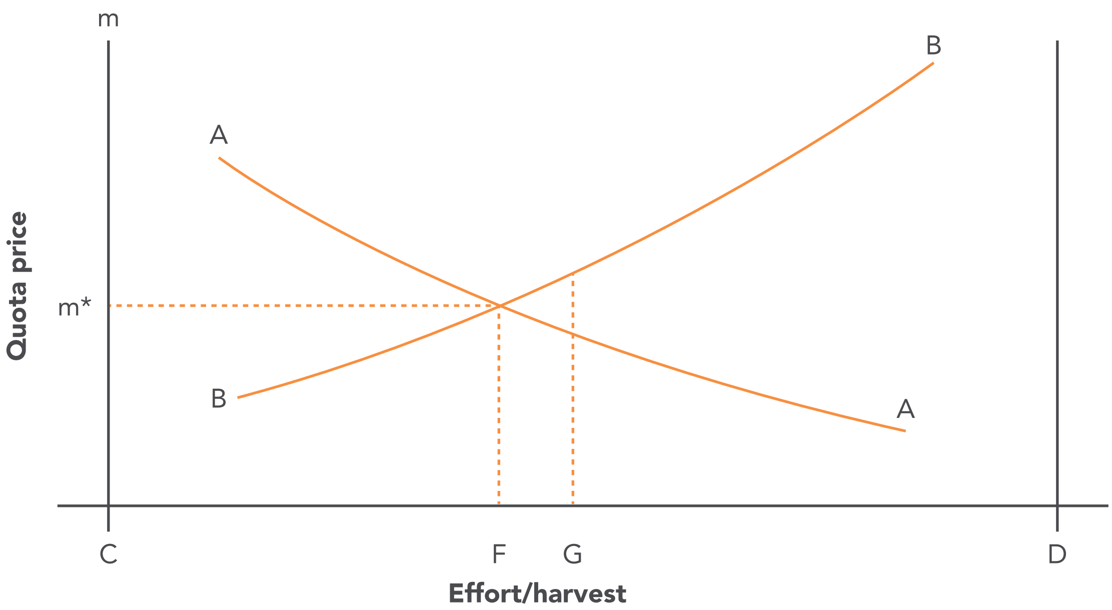


Figure 3.4. Two firms' demand for quotas as a function of quota price. "Effort/harvest" means effort quota or harvest quota.

for effort quotas the firm wants to buy more quotas the cheaper they are; the firm may be a multi-vessel company, a single vessel company or an owner-operated vessel. The downward sloping demand curve corresponds fully to the regular firm's demand for any variable input that can be bought in the market. Figure 3.4 shows the equilibrium in a quota market with two competitive firms. The quota price is shown on the vertical axis. On the horizontal axis the distance CD measures the managers' total supply of effort quotas or harvest quotas. If effort quotas are used, the total supply CD has to be less than the open access effort level to ensure demand and a positive price. If there is a positive price for effort quotas this also ensures a positive price for harvest quotas, and vice versa. In figure 3.4 quotas in firm A are measured off to the right from C and quotas in firm B are measured off to the left from D. The AA curve expresses the value of the marginal quota in firm A and the BB curve measures the value of the marginal quota in firm B. Thus the AA and the BB curves are the demand curves for quotas for firms A and B respectively. Each of these demand curves depends upon three things. First, the harvest technology for producing effort from capital, labour and other inputs. Second, the price of fish; an increase in the price shifts the demand for quota upwards. Third, the amount of vessel specific capital, which may be different for the two firms. In this case depicted in figure 3.4 there is more vessel capital in firm B than in firm A since the quota demand for any price m is higher in firm B than in firm A.

Figure 3.4 shows that the quota price m^* is the equilibrium price. For this price the total quota, equal to the distance CD, is allocated between the two competitive firms according to the profit maximising criterion.[8] If the initial quota distribution is CG for firm A and DG for firm B, both firms will gain from a quota trade. Firm A will sell quota FG to firm B, and the market equilibrium is established at F with the quota price m^*. In general, if the manager distributes for free the initial total quota CD equally between several firms, which are allowed to trade quotas, a competitive quota market ensures that the most efficient firms conduct the actual harvest. This is also the case for any other initial free distribution of the total quota. When quotas are distributed for free to the fish harvesting firms these firms reap the benefits of a successful management regime. Alternatively the manager could auction the quotas, and with a competitive market the equilibrium price is m^*, as shown in figure 3.4. The main difference between an auction and initially free quotas is in the distribution of the resource rent. With an auction the auctioneer collects the resource rent, whereas the rent benefits the recipients when quotas are distributed for free. This may explain why fishers are usually in favour of free initial quotas and why they oppose auctions.

Exercise 3.1

A fish stock with its distribution area limited to a bay is managed locally. Assume that the following function describes the annual growth of the stock:

$$F(X) = r \cdot X \cdot (1 - \frac{X}{K}),$$

where X is the stock level at the beginning of the year, r is the intrinsic growth rate and K is the carrying capacity.

When fishing takes place harvest per unit of effort is proportional to the stock level, implying the following catch function:

$$H = q \cdot E \cdot X ,$$

where H is catch, q is the catchability coefficient and E is fishing effort measured as number of vessel years. The unit cost of effort is a and p is the price of fish.

The parameter values are:

r = 0.25 per year
K = 1000 tonnes
q = 0.05 tonnes per vessel year
p = 1.00 $ per kg
a = 10 000 $ per vessel year

Find (and explain how) equilibrium effort, catch, revenues and costs for each of the following management objectives:

a) Maximise employment in fish harvesting,
b) Maximise harvest to be processed onshore,
c) Maximise resource rent of the fishery.

How could you as the manager of this fishery realise objective *c* given that objective *a* has been followed until now?

Exercise 3.2

Two firms, A and B, are profit maximisers and act as if they are price takers in a competitive quota market (it could be either harvest quota or effort quota).

M = quota price ($ per tonne or per trawl day)
X = quota (tonnes or trawl days)

The demand functions for quotas differ between the two firms, and are:

$$m_A = 1000 - 0.015X_A$$
$$m_B = 1200 - 0.010X_B$$

1. What is the marginal value of quota for each firm (m_A and m_B) if the total quota $X = 50\ 000$ is distributed between A and B, with $X_A = 20000$ and $X_B = 30000$?
2. What is the competitive equilibrium quota price ($m^* = m_A = m_B$) and the corresponding quota for each firm (X_A and X_B), assuming that quotas are fully utilised?
3. What is the traded quota (the difference between the initial distribution and the competitive equilibrium) for each firm?
4. Draw a picture of what you have derived in question 1–4 based on the information above (tip: see figure 3.4) and mark on the axis the numbers you have found.

What is the efficiency gain from trade, in $ and in % of the equilibrium value of the total quota?

Exercise 3.3

In a fishery the long-run harvest function (harvest volume) is

$$H(E) = aE - bE^2$$

a,b positive constants, E is fishing effort. Total cost is

$TC(E) = cE$, with c = unit cost of effort and

Total revenue is $TR(E) = pH(E)$, with p = constant price of fish.

a) Find the open-access equilibrium values of effort and harvest, E_∞ and H_∞, respectively.
b) Find the fishing effort that maximizes resource rent, E_{MEY}, and the corresponding harvest, H_{MEY}. What happens to E_{MEY} and H_{MEY} if p increases?
c) Find the fishing effort that maximizes sustainable yield (harvest), E_{MSY}.
d) With the parameters a = 30, b = 0.02, c = 100 and p = 10, calculate E_∞, E_{MSY} and E_{MEY}. Does this imply biological overfishing or not?
e) The fisheries management board levy a tax per unit fishing effort, t_E = 100. What will the fishing effort be in this case? Does this imply biological overfishing or not?

4 INVESTMENT ANALYSIS

To fish down or to build up a fish stock takes time, and time is money for enterprises and consumers. In this chapter we introduce the concept of discounting and analyse how a positive discount rate affects the optimal long-run harvest and stock level, as well as the fishery in transition. Both discrete and continuous time frameworks are used.

4.1 DISCOUNTING

In the previous chapter we discussed resource rent in an open access and in a maximum economic yield fishery, and showed that open access implies dissipation of the potential resource rent due to excessive effort and too low stock level. To change from open access to maximum economic yield fishing necessitates reduced effort and increased stock level. However, rebuilding a fish stock takes time since the resource itself has a limited reproductive and growth capacity. Rebuilding can only take place if harvesting is reduced or stopped for some time since harvest has to be less than natural growth to generate growth in the stock. At any point in time the resource manager has the choice between depletion, rebuilding and equilibrium harvesting of the fish stock. Depletion means that harvest is greater than natural growth, and revenue is high in the short run. However, this harvest strategy is not viable in the long run and will have to be changed after some while to avoid economic losses.

Rebuilding a fish stock means investing the foregone harvest, thus, revenue is reduced in the short run with the aim of getting more in return at a later stage. In this case a part of the potential net revenue is invested in the fish stock, the natural resource capital, to save for future purposes. For the resource owner, usually the society, the question at any point in time is whether to consume or invest. For an investment in the stock to be profitable, the return on this investment should be just as good or better than for other investment projects. A sum of money to be received in the future is not of the same value as the same sum of money received today, since money could be deposited in the bank at a positive interest rate. Thus, the interest rate plays an important role in the evaluation of investment projects as well as in comparison of the value of money at different points in time.

Before we proceed to study capital management of the resource stock, let us recapitulate the main connections between present value and interest rate in a discrete and a continuous time context. (Now you should have a quick look at this sub-chapter. If you already knows this you may go directly to chapter 4.2.)

When investing A_0 dollars, for example as a bank deposit, at an annual interest of i per cent, your capital will after one year have grown to $A_0(1 + i)$ and after two years the value will be $A_0(1 + i)^2$. In general, an investment of A_0 dollars on these conditions will after t years have the following value

$$A_t = A_0(1+i)^t. \tag{4.1}$$

Solving equation (4.1) for A_0 gives

$$A_0 = \frac{A_t}{(1+i)^t}. \tag{4.2}$$

This shows the connection between the future and the present value of money. A_t dollars in t years is worth A_0 at the present, therefore, A_0 is called the present value of A_t. It is easy to see from equation (4.2) that the present value of a given amount of future money is lower the farther in the future it will be received and the higher the interest is. For businesses and people investing their money, i is usually called the interest rate or market rate of interest, whereas in economic analysis it is often called the social rate of discount. The factor $1/(1 + i)^t = (1 + i)^{-t}$ of (4.2) is the discount factor, which has a value less than one for all positive values of i and t. For $t = 0$ the discount factor equals one and it decreases for increased values of t. This means that money at the investment or loan point in time is not discounted, whereas all future money is. Note that the discount factor approaches zero when t goes to infinity. This means that money values in the very, very far future hardly have any value today if they are discounted. The present value of a stream of future annual profit is the sum of the present value of each of them. For example, with an annual interest rate of 5 per cent the present value of a profit of \$1000 a year for the next five years, starting one year from now, is *0.952 · \$1000 + 0.907 · \$1000 + 0.864 · \$1000 + 0.823 · \$1000 + 0.784 · \$1000 = \$4330*. (The author has made a deliberate mistake for one of the discount factors – find this by use of your calculator).

Traditionally, discrete time formulas as discussed above are commonly used in investment and economic analysis. This is due to the fact that usually interest is calculated and firms report economic results to owners and tax authorities on an annual basis. However, in principle the period length for interest and present value calculations may be arbitrarily chosen as long as the interest rate is adjusted accordingly. For use in population dynamics and natural resource economics it is often useful to calculate growth and decay on a continuous time basis using the instantaneous annual rate of discount, δ. The relationship between the discrete time annual interest rate and the instantaneous rate of interest is

$$(1+i)^{-t} = e^{-\delta t}, \tag{4.3}$$

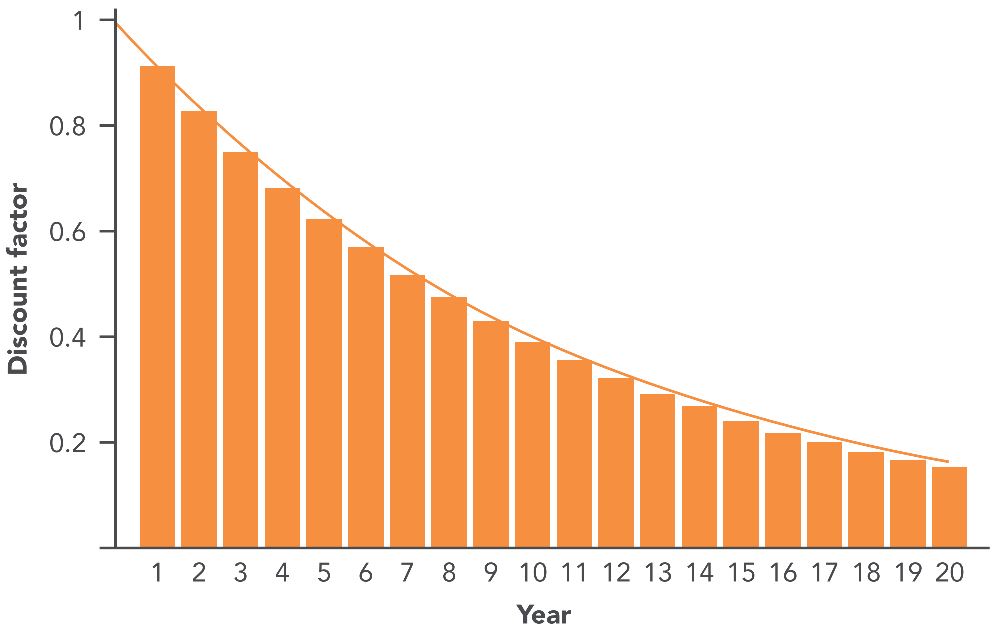


Figure 4.1 Discount factors for discrete (bars) and continuous (curve) time, with $i = 0.10$ and $\delta = 0.0953$.

where e = 2.71828 is the base of the natural system of logarithms. Figure 4.1 shows the connection between discount factors for i = 0.1 and δ = 0.0953 using discrete and instantaneous time, respectively, on an annual basis. From (4.3) we derive, by taking the natural logarithm of both sides,

$$\ln(1+i) = \delta. \tag{4.4}$$

For i = 0.1 we derive δ = 0.0953 by using (4.4). For bank deposits, using the annual rate of interest i, compound interest is usually calculated at the end of each year. However, using the instantaneous rate of interest δ implies that interest on interest is calculated on a continuous basis throughout the year. That is why δ is less than i – the continuous calculated interest on interest compensates for the lower value of the proper interest rate (δ compared to i). Note that this discussion is based on a time step of one year in the case of discrete time. If, however, we use a shorter time step, the difference between i and δ, according to equation (4.4), will be smaller. In the extreme case when the time step approaches zero, the discrete time rate of interest, i, will approach the continuous time rate of interest, δ.

As noted above, formula (4.2) is for the discrete time case. Using continuous time in the corresponding formula for computation of the present value A_0 of the future value at time t, $A(t)$, we get

$$A_0 = A(t)\, e^{-\delta t}. \tag{4.5}$$

Whether one should use discrete or continuous time approach in economic analysis of investment is primarily a question of convenience. The formulas (4.2) and (4.5) give the same result as long as i and δ are in accordance with (4.4). In theoretical analysis it seems that the continuous time approach is the preferred one, whereas in empirical work discrete time calculations are the most common. The fact that most fish stocks are assessed at regular time intervals is a practical argument for using discrete time models in studies of applied fisheries biology and fisheries economics.

4.2 FISH STOCKS AS CAPITAL

At any point in time the resource manager has a choice between depleting, rebuilding and equilibrium harvesting of the fish stock. These options imply that the harvest has to be either above, below or equal to the natural growth of the stock. Globally many fish stocks are overexploited and the policy objective is to rebuild them (FAO, 2010). Such rebuilding means an investment in the natural capital. To assure profitability of an investment in a fish stock the present value of postponing the harvest has to be greater than the value of immediate harvest. In case of actual management the options are usually "greater" or "smaller" harvest now compared with "smaller" or "greater" future harvest, or change in harvest. However, to simplify the analysis let us start by comparing two distinct options, A and B. For option A there is an equilibrium harvest in all periods, with a constant harvest equal to the natural growth of the stock in the initial period. For option B there is no harvest in the initial period, period 0, and the natural growth of this period is invested in the stock with the aim of increasing the potential harvest in all succeeding periods. Therefore, for option B equilibrium fishing takes place such that natural growth is harvested from including period 1. With H denoting harvest and X fish stock, the two options are

$$\text{Option A: } H_0^{\ A} = H_1^A = H_2^{\ A} = \cdots = F(X_0^{\ A}) \text{ , and}$$

$$\text{Option B: } H_0^{\ B} = 0,\ H_1^{\ B} = H_2^{\ B} = \cdots = F(X_1^{\ B}) \text{ ,}$$

where superscript denotes harvest option and subscript denotes harvest period. To compare the economic results of the two alternatives, the net economic result of each harvest period is discounted to the starting point, period 0. The fish price, p, is given at the world market whereas the unit cost of harvesting, c, depends on the stock size in the following way

$$c = c(X), \quad c'(X) < 0, \quad c''(X) > 0. \tag{4.6}$$

In other words, the unit cost of harvest, for example $ per kg, diminishes with increased stock level. The resource rent for each period of time is

$$\pi_t = (p - c(X_t))H_t, \quad t \in [0, \infty). \tag{4.7}$$

The two sets of resource rent we are going to compare are

$$\begin{aligned} &\text{Option A}: \quad \pi_0^A = \pi_1^A = \ldots = \pi_\infty^A = \pi^A, \text{ and} \\ &\text{Option B}: \quad \pi_0^B = 0,\ \pi_1^B = \ldots = \pi_\infty^B = \pi^B. \end{aligned}$$

Note for option B the zero harvest and zero resource rent of the commencement period. Compared with option A, this will increase the stock level and the harvest potential for all subsequent periods. Now the question is: when is option B to be preferred to option A? To answer this let us try to derive a criterion, or rule, for when to invest in the stock. The analysis will conclude with the investment rule in (4.12).

The difference in resource rent between options B and A from and including period 1 is

$$\Delta\pi = \pi_t^B - \pi_t^A = \pi^B - \pi^A, \quad t \in [1, \infty). \tag{4.8}$$

Recall that $\pi_0^A = \pi^A$, whereas $\pi_0^B = 0$. Assuming that the period length is one year, i designates the annual rate of discount. It is of course possible to use any period length as long as the interest rate i is adjusted accordingly. Nevertheless, we shall in this section think of one year as the period length. The present value of the future n-period resource rent differences is

$$\Delta PV = \frac{\Delta\pi}{1+i} + \frac{\Delta\pi}{(1+i)^2} + \ldots + \frac{\Delta\pi}{(1+i)^n}. \tag{4.9}$$

Since a fish stock has the potential of living eternally we need the infinite horizon equivalent of (4.9). This is easily derived by letting n approach ∞ in formula (4.9), thus the right-hand side changes to an infinite horizon geometric series. According to the formula for an infinite geometric series, we have $a + ak + ak^2 + \ldots\ldots + ak^{n-1} = a/(1-k)$, when $k < 1$ and $n \rightarrow \infty$ (see, for example, Berck and Sydsæter, 1991). Defining

$$a = \Delta\pi/(1+i)$$

and

$$k = 1/(1+i)$$

we derive

$$\Delta PV = \frac{\Delta \pi}{i} \ . \tag{4.10}$$

(the student should check that this is correct). We have now found, in (4.10), that by not harvesting during the starting period, thus investing the value π_0^A in the stock, the additional present value of future harvests equals the additional annual value divided by the annual rate of discount. The important question now is: is this a profitable investment for the resource owner? According to the standard investment criterion, the investment is profitable if there is a positive difference between present value of future profit due to the investment and the initial investment. Therefore, in our case the investment is profitable if

$$\frac{\Delta \pi}{i} - \pi^A > 0. \tag{4.11}$$

Rearranging (4.11), we derive the following investment rule:

Invest in the fish stock if

$$\frac{\Delta \pi}{\pi^A} > i. \tag{4.12}$$

This investment rule says that the resource owner should invest in the stock as long as the relative profitability of the fish stock capital is greater than that of alternative investments expressed by the annual rate of discount, *i*. This result also implies that the optimal stock level is established when the left-hand side expression of (4.12) equals the annual rate of discount. Thus, the long-run optimal stock level may be found from the formula

$$\frac{\Delta \pi}{\pi^A} = i. \tag{4.13}$$

At the optimum the relative profitability of the fishery, based on the notion of resource rent, should equal the annual rate of discount. Further investment in the resource will reduce the unit cost of harvesting, according to (4.6). However, sustainable yield and revenue will become relatively smaller and smaller due to the shape of the growth function, $F(X)$ (see figure 2.1). The resource rent on the left-hand side of (4.13) consists of both revenue and cost elements, which may vary differently with a change in the fish stock according to whether the stock level is lower or higher than the *MSY* level. The different elements of the resource rent and the effects of changes in the discount rate warrant further investigations.

4.3 LONG-RUN OPTIMAL STOCK LEVELS

For the discrete time analysis in section 4.2 the interest rate i was used, measuring the rate of interest per year. In section 4.1 the instantaneous rate of interest, δ, was explained and compared with the discrete time rate of interest i. The former measures compound interest, that is, interest on the accrued interest as well as on the principal, on a continuous time basis. To see the implications for the long-run optimal stock level of the interest rate, fish price, density dependent harvest cost and natural growth, we shall now use continuous time to analyse the investment issue. Instead of asking how much harvest to postpone from one period of time to the next, for example, from one year to the next, we ask how much should possibly be postponed from one moment in time to the next moment, marginally later than the first.

We shall now assume that the management objective of the resource owner is to maximise his wealth. This is somewhat different from maximising resource rent (which was discussed in section 3.2). Resource rent is a flow concept, denoted for example by $/year, whereas wealth is a stock concept, denoted for example by $. Economic flows are related to time periods, for example periods of one year, whereas wealth is related to a specific point in time, for instance 1 January in a particular year. (Note that stock in this connection means a capital stock in general and not a fish stock.) There is, however, a clear link between flows and stocks, since wealth is the present value of the net revenue for all successive periods. To see this more clearly, let $A(t)$ denote the net revenue per period of time at time t, δ the rate of discount, and V the wealth of the resource owner. Recalling formula (4.2), the wealth is

$$V = \int_0^\infty A(t)\, e^{-\delta t}\, dt \,. \tag{4.2'}$$

As noted above, the resource manager has a choice among various income streams. In making this choice the manager is basically determining an investment strategy. In a perfectly certain world, which is the kind of world we are considering, the investment decision will be affected by the opportunity cost of capital, expressed by the discount rate δ, and the ecological and economic characteristics of the fishery. A necessary condition for maximising the resource owner's wealth, expressed in (*), is that he includes the opportunity cost of capital when considering what long-run level of the fish stock he shall aim at. (This opportunity cost of capital was deliberately excluded when we discussed the MEY management objective in section 3.2.)

We shall see that the long-run optimal stock level is implicitly given by equation (4.18) and that this may be presented graphically as in figure 4.2. We shall see that equation (4.19), called the Clark-Munro rule, is the continuous time equivalent to the discrete time investment rule of equation (4.13).

Recall equation (4.13), which implicitly yields the discrete time long-run optimal stock level, and think of how it may look when we use continuous time and very small changes in the variables. As noted above, at any point in time the resource manager has the choice between depleting, rebuilding and equilibrium harvesting of the fish stock. In all three cases harvesting may be possible, but of a different magnitude. Harvesting a quantity H at any point in time creates revenues for and imposes costs on the industry. Current resource rent per unit harvest depends on the price of fish and the cost of harvesting. As in the previous analysis we shall assume a constant price of fish, p, independent of the level of harvest, and a unit cost of harvest, $c(X)$, that depends on the stock level only (see equation 4.6). Investing the proceeds at the instantaneous rate of discount, δ, implies that the sustainable interest from this harvest equals

$$R(H;X) = \delta(p - c(X))H \,. \tag{4.14}$$

Thus, the proceeds from the fishery, $(p\text{-}c(X))H$, becomes the principal of the resource owner's financial investment. Equation (4.14) expresses the sustainable net income per period of time from an instantaneous harvest H that has been converted into a perpetual investment. Note that on the left-hand side of (4.14), X is placed after the semicolon. This means that X is kept constant – thus H is the independent variable in this case.

The sustainable interest is altered by a marginal change in the instantaneous harvest and is found from equation (4.14) by taking the derivative of R with respect to H.

$$\frac{dR}{dH} = \delta(p - c(X)). \tag{4.15}$$

This marginal sustainable interest is the marginal opportunity cost of resource capital, emanating from an incremental investment in the stock since the alternative to harvesting H is to leave it in the sea as an investment in the stock. Figure 4.2 panel (b) shows dR/dH as the upward sloping curve, equal to zero at the open access stock level. The open access stock level generates zero resource rent and we see from (4.14) that this is the case when $p = c(X_\infty)$; recalling that X_∞ is the open-access equilibrium stock level. If the current harvest generates zero rent there is no surplus to invest and sustainable interest on this zero value "investment" will of course also be zero. The unit cost of harvesting is lower the higher the stock level – thus the unit resource rent, (p-$c(X)$), is higher the higher the stock level. Harvesting H now with the objective of investing the proceeds in the bank means that the initial bank deposit, the principal, is higher the higher the stock level at the moment of harvesting. With a constant rate of interest, δ, this means that the marginal sustainable interest, expressed by dR/dH in equation (4.15), portrays an upward sloping curve in figure 4.2 panel (b).

The alternative to current harvest (option A) is to leave the fish in the sea (option B), which is to invest in the stock with the purpose of harvesting at a later point in time. Such an investment may augment the natural growth of the stock and decrease the unit cost of harvesting to yield a future net gain from these two effects combined. Sustainable harvesting is when the natural growth is being harvested, that is $H \equiv F(X)$. In this case the sustainable resource rent at stock level X is

$$\pi(X) = (p - c(X))F(X), \tag{4.16}$$

where we have substituted natural growth, $F(X)$, for harvest, H. Recall that $H \equiv F(X)$ is by definition the equilibrium harvest, also called sustainable harvest, for a given

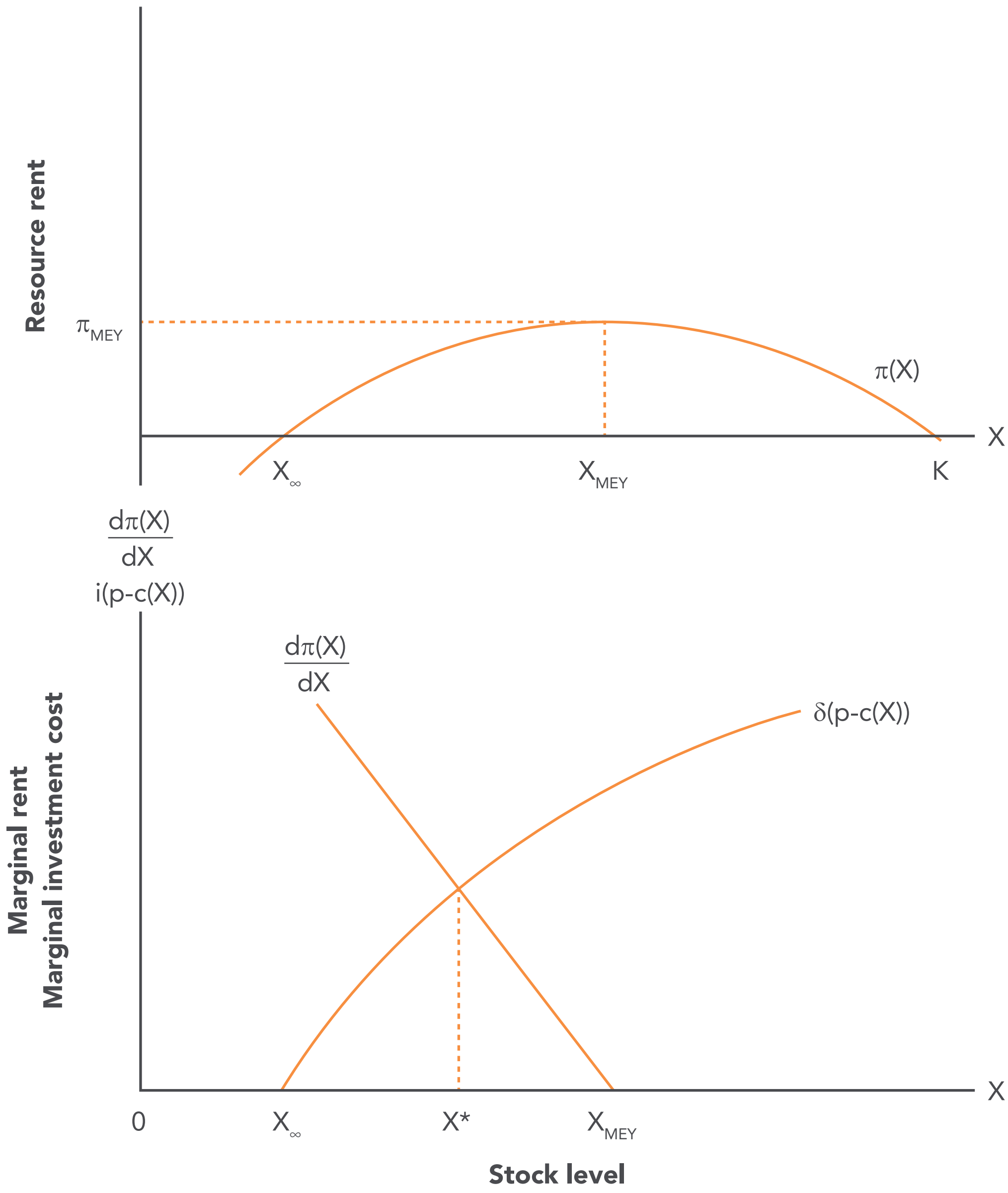


Figure 4.2 Graphical determination of the long-run optimal stock level X* (panel (b) adapted from Clark, 1976).

level of the fish stock, *X*. The sustainable resource rent, *π(X),* is portrayed in figure 4.2 panel (a). This rent has its maximum for stock level X_{MEY}, or to put it the other way around, the stock level that gives maximum economic yield is called the maximum economic yield level, X_{MEY}.

Future gain comes via two components, lowering the unit cost of harvesting and possibly increasing the sustainable yield. Let us have a closer look at these two components by taking the derivative of equation (4.16) with respect to *X*, arriving at

$$\frac{d\pi}{dX} = (p - c(X))F'(X) - c'(X)F(X). \tag{4.17}$$

This is the marginal sustainable resource rent, portrayed in figure 4.2 panel (b) as the downward sloping curve. This may be interpreted as the "revenue" side of the investment budget – the net revenue resulting from a marginal investment in the fish stock. It is not obvious from equation (4.17) why $d\pi / dX$ is downward sloping. However, note that $d\pi / dX$ is the slope of the sustainable resource rent $\pi(X)$, defined in equation (4.16) and depicted in figure 4.2 panel (a). This panel shows that the slope of the $\pi(X)$-curve, the marginal sustainable resource rent, is positive but decreasing with increasing stock level between the open-access level, X_∞ and the maximum economic yield level, X_{MEY}. Therefore, investing one tonne of fish in the stock, that is, to increase the stock level by one tonne, gives a higher economic return for stock levels closer to X_∞ than close to X_{MEY}.

The marginal sustainable resource rent consists of two terms (on the right-hand side of equation 4.17). The first term is the instantaneous marginal product of the stock, $F'(X)$, evaluated at the net price, or resource rent per unit of harvest, $[p - c(X)]$. This term expresses the partial net gain for the fishery due to a change in the sustainable yield from a marginal increase in the stock level. Recall that $F'(X)$ may be positive or negative, for stock levels below or above, respectively, the MSY level (see equation 2.1). The second term of the right hand side of (4.17) is related to the cost saving effect of increasing the stock level. Note that this is always positive due to the minus sign and the negative value of $c'(X)$ (see equation 4.6).

From an investment point of view there has to be a balance between the profitability of investing (proceeds from the harvest) in the bank and abstaining from harvesting to invest in "fish in the sea" (to increase the fish stock level). Thus, the marginal profitability of these two types of investment has to be equal to ensure a balanced portfolio. Equating equation (4.15) and (4.17) gives

$$(p - c(X^*))F'(X^*) - c'(X^*)F(X^*) = \delta(p - c(X^*)) . \tag{4.18}$$

where X^* denotes the long-run optimal stock level, implicitly given by this equation. In our case equation (4.18) has a unique solution for $X = X^*$, the optimal equilibrium stock level, shown in figure 4.2. We have discussed above the economic significance of each of the two sides of equation (4.18). It is easy to see from figure 4.2 that an increase in the discount rate, δ, will reduce the optimal stock level. Such an increase will turn the upward sloping curve anti-clockwise around X_∞, thus moving the intersection point towards the left. Increased δ means that the opportunity cost of investments rises, making it more costly to keep a large capital stock, the fish stock, in the sea. If δ goes towards infinity, which implicitly is to say that the manager sets a zero value on future revenues, the optimal stock level goes towards the open-access level X_∞. This is precisely what fishers in an open-access fishery are confronted with. For each fisher the opportunity cost of investing in the stock by abstaining from harvest is infinitely high. What Peter possibly saves in the sea for his future use will be harvested by his competitors, including Paul and Mary, to yield zero return on his savings. This is why Peter, and each of the other fishers, is forced by the open-access regime to behave in a myopic way to catch as much as possible at any point in time.

Having discussed the effect of an infinitely high discount rate we now turn to the other extreme, a discount rate equal to zero. Figure 4.2 panel (b) shows that the upward sloping curve, showing the marginal sustainable opportunity cost of investment, will turn clockwise around X_∞ when δ decreases. This moves the optimal stock level X^* towards the maximum economic yield level, X_{MEY}. Thus if future revenues are not discounted relative to current revenue, which is the meaning of $\delta \rightarrow 0$, the capital theoretic approach to management reduces to that of maximising the resource rent. In this case a sacrifice of current harvest for future gains causes less "pain" since future gains last forever without being discounted. One $ next year, or in 20 years, is just as good as one $ today.

Our analysis of the effect of discounting on the long-run optimal stock level is a simplified approach to capital-theoretic analysis of fisheries management. The development around 1970 of the mathematical tool of optimal control theory, an extension of the standard calculus of variations, made it possible to analyse dynamic economic issues in a more thorough way than had previously been done. Control theory was applied to analysis of economic growth, capital investment, natural resource management and other issues that included evaluation of income across time. Several studies of capital theoretic analysis of fisheries appeared in the early 1970s (for a review, see for example, Munro and Scott, 1985). In 1975 two Canadian researchers, a mathematician, Colin W. Clark, and an economist, Gordon R. Munro, published one of the most quoted fisheries economics papers ever (Clark and Munro, 1975) which led to the investment rule in equation (4.19). In a recent article theses authors reviews the earlier attempts to incorporate the theories of capital and investment into fisheries economics and argues that such dynamic analysis is now of immediate policy relevance (Clark and Munro, 2017). Professors Clark and Munro were honored as joint recipients of the 2016 International Institute of Fisheries Economic and Trade's (IIFET) Fellow Award, presented at the organization's 18^{th} biennial conference held in Aberdeen, Scotland, July 11-15th, 2016, where an earlier version of this 2017 article was presented. http://oregonstate.edu/dept/IIFET/awards.html

Note that if we divide with the resource rent per unit of harvest, $[p - c(X)]$, on both sides of equation (4.18) we arrive at

$$F'(X^*) - \frac{c'(X^*)F(X^*)}{p - c(X^*)} = \delta. \tag{4.19}$$

Equation (4.19) is the continuous time equivalent to the discrete time equation (4.13) for computation of the long-run optimal fish stock level in steady state. The left-hand side of (4.19) is the fish stock's own rate of interest, and this equals the social rate of discount (which may or may not be equal to the market rate of interest) on the right-hand side. The stock's own rate of interest consists of two parts, first, the instantaneous marginal product of the resource, $F'(X)$, which can be positive, negative or zero. Second, it includes what has been termed the marginal stock effect,$-c'(X)F(X)/(p - c(X))$, which is always positive since $c'(X)$ is negative. The marginal stock effect has a positive effect on the optimal long-run stock size. If the unit cost of harvesting, $c(X)$, is high this implies a higher optimal stock level. The same result applies if the absolute value of the marginal unit cost of harvesting, $|c'(X)|$, is large. In some cases it may be that the marginal stock effect is great enough to imply an optimal stock level high enough to have $F'(X) < 0$ (see equation 4.19). This means that the optimal stock level may be above the maximum sustainable yield level, despite the use of discounting. It is also seen from equation (4.19) that if the unit cost of harvest is completely insensitive to stock changes, that is $c'(X) = 0$, the Clark-Munro rule reduces to the simple marginal-productivity rule $F'(X) = \delta$. In this special case the fish stock's instantaneous marginal productivity equals the marginal opportunity cost of capital, the social rate of discount, δ. Theoretical reasoning and empirical work have shown that the marginal stock effect is weak for schooling pelagic species, often fished with purse seine, and stronger for demersal species, often fished with bottom trawl or gill-net. Herring (*Clupea sp*.) and Anchoveta are examples of the former, and cod (*Gadus morhua*) and orange roughy (*Hoplostethus atlanticus*) are examples of the latter.

4.4 TRANSITION TO LONG-RUN OPTIMUM

We have seen that the long-run optimal stock level can be derived from equation (4.18), which is equivalent to the Clark-Munro rule in (4.19), and that this can be depicted graphically as in figure 4.2. The analysis started by comparing two investment alternatives, option A, with immediate equilibrium harvest and investment of the net proceeds in the "bank", versus option B, with no harvest during the initial period, but with equilibrium harvest from including the next period. Thus in option B the natural growth of the initial period is invested in the stock to harvest more later, whereas in option A the net proceeds of the initial period harvest are invested in the "bank" to yield future interest. To simplify the analysis we have in this approach discussed two outliers, the all (option B) or nothing (option A) fish stock investment of the initial period. However, in actual management situations there are at any point in time a wide range of possible exploitation intensities, from zero harvest, which implies investing the total natural growth in the stock, via some harvest or equilibrium harvest to different degrees of over-exploitation. The latter implies running down the fish stock. In a complete theoretical analysis there is usually a connection between the long-run optimum and the optimal path towards equilibrium. Nevertheless, for practical and pedagogical reasons we have discussed these two issues separately, as if the optimal long-run stock level implicitly is given by equation (4.18).

Figure 4.3 shows two possible recovery strategies in case of an overfished stock, that is, when the initial stock level is below the optimal level. Path (i) is the non-fishing adjustment path, also called the bang-bang approach to fisheries adjustment. In this case the fishery is totally closed down (panel b) and the stock recovers at its maximum speed (panel a), limited by its natural rate of growth, until time t_1 when the optimal stock level is reached. From time t_1, long run optimal harvesting, H^*, takes place at stock level X^*. The gradual adjustment path, path (ii) in Figure 4.3, which allows some harvesting during the stock recovery period, goes on until time t_2, with the implication that it takes somewhat longer for the stock to reach its optimal equilibrium level.

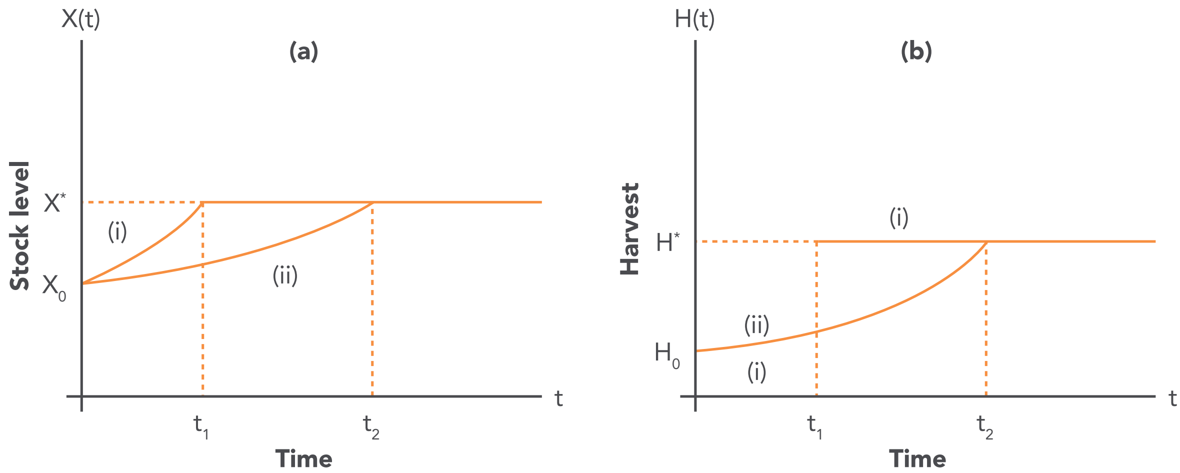


Figure 4.3 Strategy (ii) implies some fishing during the transition period and a slower rebuilding of the stock than strategy (i), which is the bang-bang strategy with complete closure of the fishery for some time.

In figure 4.3 the difference between strategy (i) and (ii), with respect to harvest and stock recovery, is found during the adjustment period up to t_2. However, from t_2 to infinity the long-run optimal harvesting takes place regardless of the transition period strategy. Therefore, for an evaluation of the costs and gains of the alternative rebuilding strategies, it suffices to compare performances of the transition period, that is, until t_2. Strategy (ii) gives the highest catch in the first part of the period up to t_1, during which strategy (i) demands total close down of the fishery. In the second part of the transition period, between t_1 and t_2, strategy (i) gives the highest catch, equal to the long run optimum, H^*. If the price of fish is constant, regardless of quantity harvested, and the unit cost of harvesting depends on stock level only, as given in (4.6), the bang-bang strategy is superior to any other strategy (see Clark and Munro, 1975). This implies that any strategy postponing the moment for equilibrium harvesting beyond t_1, for example, to t_2, is an inferior solution. The present value of resource rent from harvesting will be highest with the bang-bang strategy, given the two crucial assumptions regarding price of fish and unit cost of harvesting. The reason for this is that there are no price and unit cost penalties from reduction of harvest and effort, neither from the market in the form of forgone opportunities for gaining a higher price with smaller harvest, nor from any effort-dependent unit cost of harvesting. (The case of price and cost characteristics that may lead to more gradual transition paths than the bang-bang path is discussed below.)

So far we have discussed transition as if path (ii) in figure 4.3 is the only alternative to the bang-bang path (i). However, this is just for illustrative purposes. In empirical work and actual management it could be that several alternative paths are closer to optimum than the bang-bang path. In figure 4.3 panel (b), path (ii) depicts a gradual increase in harvest during the transition period, from H_0 at the commencement of the transition to the equilibrium harvest, H^*, at the end. Alternatively we may for instance start with a catch somewhat larger than H_0 and keep this constant until the optimal equilibrium stock level is reached. Another alternative is to start with a harvest somewhat lower than H_0 and stay below harvest path (ii) throughout the transition period. This implies that the stock will grow faster than shown for stock path (ii) of figure 4.3 panel (a), and t_2 will be moved to the left to shorten the time necessary to rebuild the stock to the optimal level X^*.

If the price of fish varies with harvest, as is the case with a downward sloping demand curve, this may have an effect on the optimal transitional fishery. In this case the optimal path is usually a more gradual transition to the long-run equilibrium in order to benefit from the high price-low quantity combination. Thus, the bang-bang solution with complete closure of the fishery during the transition period is no longer optimal. The reason for this is that the positive economic effects of a small harvest at a higher average price throughout the transitional period will be beneficial compared with the negative effect from delaying the moment of time we reach a fully restored fishery. Related to figure 4.3, this means that the point in time when the optimal equilibrium stock level and harvest are reached, t_1, is postponed somewhat, for example to t_2.

If harvest costs are different from what we assumed above (see equation 4.6), this also may imply an optimal transition path different from the bang-bang approach (i), towards a more gradual transition path illustrated by (ii) in figure 4.3. For instance, if the unit cost of harvesting depends not only on the stock level, but also on effort or on harvest level, this may switch the optimal transition path from bang-bang to more gradual stock recovery. The existence of some high-liners, that is, fishers who are significantly more cost-effective than the average, could be an argument for letting this type of effort continue harvesting during the rebuilding of the fish stock. In other words, if effort is heterogeneous it may be an advantage for the realisation of resource rent, in present value terms, to operate a minor fishery with the most cost-effective effort rather than closing down the fishery during the transition period. (We shall return to the issue of high-liners and intra-marginal rent in chapter 7).

4.5 ADJUSTED TRANSITION PATHS

We have seen above that economically over-fished stocks need reduction or complete cession of harvesting to recover and grow to the optimal level. Temporary reduction in harvest also requires a reduction in fishing effort. Since effort is composed of, or produced from, labour, variable inputs like fuel, bait and gear, as well as vessel capital, the reduction of effort will have repercussions on the labour market and the markets for other inputs. The consequences of these changes are most severe in areas dependent on fishing with few alternative employment opportunities. The same applies to the negative effects of reduced quantities of fish as raw materials for the fish processing and marketing industries, often called the post-harvesting sector. For owners and employees of this sector there may be both economic and social costs incurred because of fluctuations in landings of fish, in particular when landings are reduced. Therefore, rebuilding of fish stocks is not possible without temporary negative effects on employment, the vessel service industry and the post-harvest industry. However, the short- and medium-term costs of industries and society should be outweighed by future gains from higher stock levels, otherwise fish stock investment is futile.

The objectives of actual fisheries management often include elements other than resource rent or net revenue of the industry. For example, such objectives are included in the

Code of Conduct for Responsible Fisheries, adopted in 1995 by the Food and Agriculture Organisation of the United Nations (FAO), shown in Box 4.1.

Box 4.1 FAO Management Objectives

Recognising that long-term sustainable use of fisheries resources is the overriding objective of conservation and management, States and subregional or regional fisheries management organisations and arrangements should, inter alia, adopt appropriate measures, based on the best scientific evidence available, which are designed to maintain or restore stocks at levels capable of producing maximum sustainable yield, as qualified by relevant environmental and economic factors, including the special requirements of developing countries.

Such measures should provide inter alia that:

- *a. excess fishing capacity is avoided and exploitation of the stocks remains economically viable;*
- *b. the economic conditions under which fishing industries operate promote responsible fisheries;*
- *c. the interests of fishers, including those engaged in subsistence, small-scale and artisanal fisheries, are taken into account;*
- *d. biodiversity of aquatic habitats and ecosystems is conserved and endangered species are protected;*
- *e. depleted stocks are allowed to recover or, where appropriate, are actively restored;*
- *f. adverse environmental impacts on the resources from human activities are assessed and, where appropriate, corrected; and*
- *g. pollution, waste, discards, catch by lost or abandoned gear, catch of non-target species, both fish and non-fish species, and impacts on associated or dependent species are minimised, through measures including, to the extent practicable, the development and use of selective, environmentally safe and cost-effective fishing gear and techniques.*

States should assess the impacts of environmental factors on target stocks and species belonging to the same ecosystem or associated with or dependent upon the target stocks, and assess the relationship among the populations in the ecosystem.

FAO (1995), pp. 9–10.

The Code, which is voluntary, was developed by FAO and its member countries as a response to the economic and ecological failure of several fisheries worldwide. Certain parts of it are based on relevant rules of international law, including those reflected in the United Nations Convention on the Law of the Sea of 10 December 1982. From an economic point of view the main objective of "…*maximum sustainable yield, as qualified by relevant environmental and economic factors*…" is a little bit strange. However, instead of further interpretation of this agreed FAO text, let us anticipate that the manager, on his own or together with the industry and other stakeholders, does the thinking, specifies the management objective(s) and in the end arrives at a long-run target level for the fish stock. Let us call this level the target stock level, with the corresponding target harvest and effort level as well.[9] The target stock level may be above, equal to or below the optimal stock level discussed above.

The transition costs and benefits depend on the objectives of policy makers (for example, economic, biological, social, and administrative) and on the characteristics of the instruments (technical measures, input and output controls) that are used to achieve their objectives. The objectives pursued by fishery managers, and the management measures that are used to achieve these objectives will thus play an important role in determining the costs and benefits incurred in a transition to targeted fisheries.

Taking the development of the stock towards a long-run target as a guiding principle, it is possible to evaluate the benefits and costs associated with this transition. If a stock is not realising its production potential because it is too small, then harvest opportunities are being forgone. Potential harvest that could be generated by the stock is not being realised, due to its depleted state. Figure 4.4 provides a stylised illustration of the adjusted transition path. Panel (a) shows the harvests from the fish stock, panel (b) shows the effort levels associated with harvesting the stock over time and panel (c)

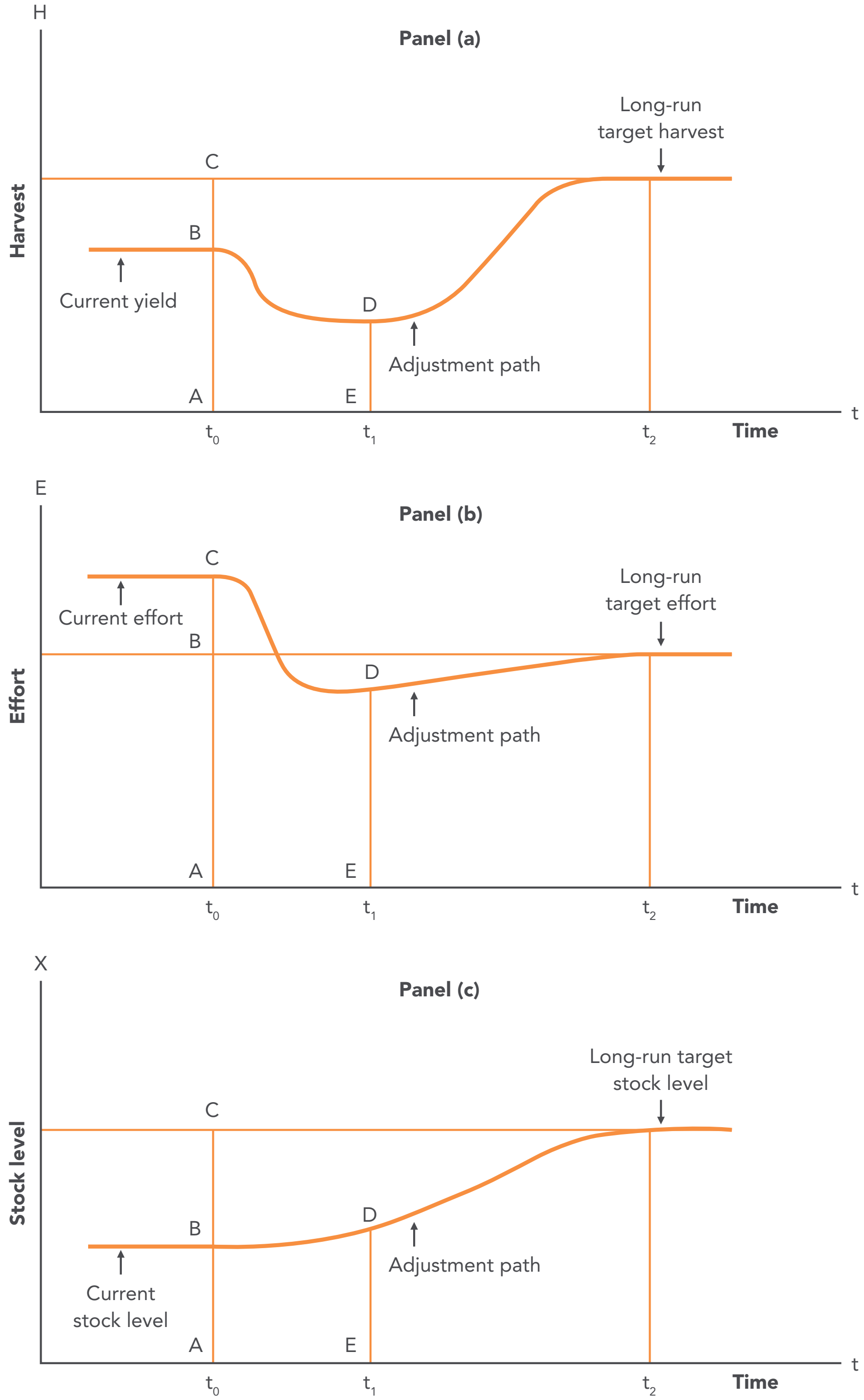


Figure 4.4 Stylised adjusted targets and transition paths for stock level, effort and harvest of a fishery.

shows the change in the stock level over time. In comparison with a fishery being managed at its target levels, time t_0 is characterised by lower harvest, higher effort and smaller stock size. If the stock were given a chance to rebuild, a larger harvest with lower level of effort could be realised. The line CB in panel (a) shows harvest forgone due to the depleted state of the stock.

Figure 4.4 also illustrates the principle of the transition period's pains discussed above. If managers enact remedial measures to allow fish stocks to rebuild, then harvest and effort need to be reduced during the transition period. Instead of continuing to harvest AB in panel (a), harvest needs to be reduced to DE. Figure 4.4 panel (b) illustrates the reduction in effort that is required. Effort needs to fall below that associated with the long-run target if the stock is to rebuild.

The movement over time from t_1 to t_2 illustrates the final stage of the transition process. As the size of the fish stock increases towards the target level, harvest can increase. Due to the increased abundance of fish, the effort required to harvest this level of yield would be relatively lower than that before the transition period started. A recovered fishery is characterised by relatively higher catch, larger stock and lower effort.

The benefits and costs of a transition to targeted fisheries also depend on the resource's biological characteristics. In the case of short-lived species, stocks that have been overfished may rebound to target levels in a relatively short period of time. In the case of species with low fertility or that grow slowly, recovery may take a significant amount of time, in which case the benefits associated with the transition will only be incurred in the more distant future. Indeed it is possible that the discounted costs could outweigh the benefits.

Exercise 4.1

Two fisheries, A and B, generate annual sustainable resource rent Π^1 (million €) as shown in the table. By closing the fishery completely for one year the stock is allowed to recover somewhat and the annual sustainable resource rent increases to Π^2.

Table 4.1

	A	B
Π^1	11.00	0.90
Π^2	11.50	1.05

1. Would you as the manager recommend this one-year closure of the fishery when the social rate of discount, at an annual basis, is 7%?
2. What size of the discount rate could make it worthwhile to close both fisheries for one year?

Exercise 4.2

1. Show that the present value, *PV*, of an eternal constant annual flow of income, *A*, equals $PV = \int_0^{\infty} A\, e^{-\delta t}\, dt = \frac{A}{\delta}$.

2. A resource economic investment project gives eternal net revenue of 10 million USD per year. What is the net present value of this project when the annual discount rate is 5% or 10%?

5 THE GORDON-SCHAEFER MODEL

This chapter discusses the Gordon-Schaefer model for analysis of open-access and optimally managed fisheries. The main differences between this and the previous chapters are derived from the use here of a specific form of the natural growth function. This allows us to find exact expressions for equilibrium levels of the fish stock, effort, revenues, costs and resource rent.

5.1 THE LOGISTIC GROWTH MODEL

Most fish stocks are such that natural growth is small for both high and low stock levels and largest for some intermediate level. The reasons for this are mainly density- dependent biological factors, such as individual growth and natural mortality. In the previous chapters we have used a bell-shaped graph for natural growth as a function of stock size. Now we are going to use the logistic growth function, which is a mathematical representation of biomass growth of an animal stock, and this depicts a symmetric bell-shaped natural growth curve.

Stock change per unit of time is

$$\frac{dX}{dt} = F(X) - H, \tag{5.1}$$

where $F(X)$ is natural growth and H is catch. The Gordon-Schaefer model, named after the works of two Canadian researchers (economist H. Scott Gordon (1954) and biologist M.B. Schaefer (1957)), is based on the logistic type natural growth equation

$$F(X) = rX(1 - X/K) \tag{5.2}$$

Equation (5.2) was designed and discussed first by P.F. Verhulst (1838), and later re-discovered by R. Pearl (1925). Parameter r is the maximum relative growth rate, also called the intrinsic growth rate, and K is the carrying capacity, both parameters assumed to be fixed. The reader should verify that the relative natural growth is a linear function of the stock level and approaches its maximum, equal to r, when the stock level goes to zero, that is $F(X)/X$ approaches r when X approaches zero. Parameter r is mainly related to the actual species we are studying while K depends on mainly the natural environment of the stock, such as size and biological productivity of the habitat. Equation (5.2) is quadratic in X and for low stock levels the first part with the positive sign is dominating, whereas for higher levels the second part, with the negative sign, is dominating. Natural growth is usually positive, but may even be negative if the stock level for any reason is higher than K. However, negative natural growth can for obvious reasons not represent biological equilibrium, with dX/dt = 0 in (5.1), neither with nor without harvesting.

Natural growth has its maximum for a specific stock level that may be found by maximising $F(X)$ with respect to X. This stock level produces the maximum sustainable yield (MSY), and the student should verify that this equals

$$X_{MSY} = K/2. \tag{5.3}$$

Substituting X_{MSY} for X in equation (5.2) gives

$$MSY = F(X_{MSY}) = rK/4. \tag{5.4}$$

Thus the maximum sustainable yield equals a quarter of the product of the two parameters.

The Gordon-Schaefer model includes natural growth, according to the law of equation (5.2), and harvest according to

$$H = qEX \tag{5.5}$$

that we recall from chapter 2. This harvest function has the property of having catch per unit of effort proportional to the stock level, with the catchability parameter q as the proportional ratio. In Schaefer (1957) catch and effort data were used to estimate changes in fish stocks.

We are now going to find the connection between harvest and effort at equilibrium for this model. Equilibrium harvesting means $dX/dt \equiv 0$ and $H \equiv F(X)$ in equation (5.1), and from (5.5) follows $X = H/qE$. Substituting this expression for X in (5.1) gives

$$H = \frac{rH}{qE}\left(1 - \frac{H}{qKE}\right). \tag{5.6}$$

Rearranging equation (5.6) somewhat gives

$$H = H(E) = qKE\left(1 - \frac{qE}{r}\right), \quad \text{when} \quad H \equiv F(X). \tag{5.7}$$

Comparing (5.7) and (5.2), we notice also that the former, the equilibrium harvest function, is a quadratic function. It is quadratic in the product qE, whereas the natural growth function (5.2) is quadratic in X. You may notice that the product qE has to be less than r to have a positive harvest, according to equation (5.7). If qE is kept at or above r the stock becomes extinct and this of course gives a zero equilibrium harvest. We are now going to use the equilibrium harvest function for an economic analysis of open access and optimally managed fisheries.

5.2 THE OPEN-ACCESS FISHERY

Let us now see if we can find the open-access effort and stock equilibrium levels expressed as functions of biological and economic parameters. This way we may analyse the equilibrium levels are affected by changes in parameter values.

When harvest is sold in a competitive market with several close substitutes, the quay price of fish, p, is hardly dependent on the quantity landed. Let us assume that p is constant. Price multiplied by quantity in (5.7) gives the total revenue

$$TR(E) = pH = pqKE\left(1 - \frac{qE}{r}\right). \tag{5.8}$$

The $TR(E)$ curve and the $H(E)$ curve are shown in Figure 5.1 panel (a) for $p > 1$. In this case the TR curve is above the H curve, but generally the graphical picture depends on the units of measurement for total revenue and harvest.

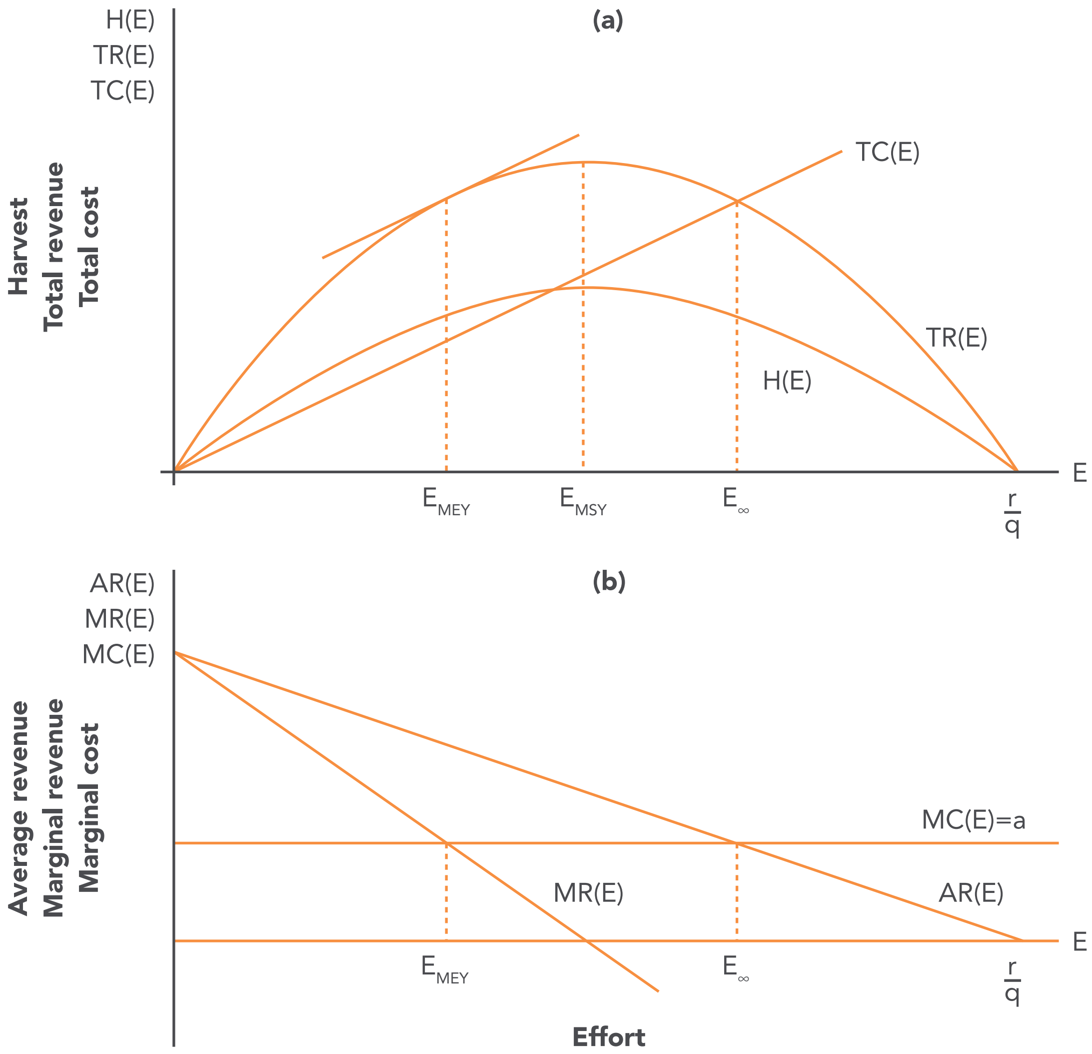


Figure 5.1. The sustainable harvest and revenue curves, as well as total cost, are shown in Panel (a), and the marginal and average revenue and cost curves of the Gordon-Schaefer model are shown in Panel (b).

Total harvest costs increase with effort, and the simplest form is when the increase is proportional. With a constant unit cost of effort, *a*, total cost equals

$$TC(E) = aE. \tag{5.9}$$

The total cost is shown as a straight line in Figure 5.1 panel (a). In this case $MC(E) = AC(E) = a$, and this is shown in panel (b). We may use equation (5.8) to find the average and marginal revenue of effort. The average revenue equals

$$AR(E) = TR(E)/E = pqK\left(1 - \frac{qE}{r}\right). \tag{5.10}$$

The average revenue curve is a straight, downward sloping line as shown in Figure 5.1 panel (b). Its maximum is for E close to zero. In this case the equilibrium stock level will be close to its carrying capacity, implying the highest $AR(E)$. The average revenue approaches zero when effort E approaches r/q. If the fishing effort is kept sufficiently large, $E > r/q$, for a long time the stock becomes extinct. This is why $AR(E) = 0$ for such high effort levels.

Let us now find the open-access effort level for the Gordon-Schaefer model. We have seen in Ch. 3, equation (3.6) that at bioeconomic equilibrium under open-access $MC(E) = AR(E)$. With total cost given in (5.9) the open-access equilibrium level of effort can be found from $AR(E) = a$ combined with (5.10). This gives

$$E_{\infty} = \frac{r}{q}\left(1 - \frac{a}{pqK}\right). \tag{5.11}$$

Thus the open-access equilibrium level of fishing effort depends on both biological and economic parameters. It is proportional with the intrinsic growth rate r, increases with fish price and carrying capacity, and decreases with effort cost. In other words, fisheries based on biologically highly productive resources with large r and K, may sustain a large fishing effort under open-access. In addition, this may be spurred on by high fish price and low effort cost. Having found the open-access effort level in (5.11) the corresponding equilibrium harvest may be found by substituting E_{∞} for E in equation (5.7).

After discussing the open-access fishing effort, let us now find the open-access equilibrium level of the fish stock. For this we will use the unit cost of harvesting and the resource rent per unit harvest. The unit cost of harvest follows by use of equations (5.5) and (5.9):

$$c(X) = \frac{TC(E)}{H} = \frac{aE}{qEX} = \frac{a}{qX}, \tag{5.12}$$

This demonstrates that the unit cost of harvest decreases with an increase in the stock size. We could say that a large stock has a cost-saving effect for the fishery.

With constant price of fish the resource rent per unit harvest is

$$b(X) = p - \frac{a}{qX}. \tag{5.13}$$

At the open-access equilibrium the stock level X_{∞} follows from $b(X_{\infty}) = 0$, and we have

$$X_{\infty} = \frac{a}{pq}. \tag{5.14}$$

We notice that in this model the open-access equilibrium stock level is a function of economic and harvest technical parameters only. No biological parameters appear in (5.15), but they do in (5.11) for the open-access effort level. It is the economic parameters, in addition to the catchability parameter, that put a downward limit on the stock level in open-access fisheries. The stock level will be small if fish is expensive and easy to catch at a low cost.

5.3 ECONOMIC OPTIMAL HARVESTING

We have seen in Chapter 3 that to maximise the resource rent, $\pi(E) = TR(E) - TC(E)$, of a fishery, it is necessary for marginal cost of effort to equal marginal revenue of effort, that is, $MC(E) = MR(E)$. This is also the case for the Gordon-Schaefer model and we shall use this condition to find, first, the effort level that maximises the resource rent, and, second, the corresponding stock level. From (5.8) we derive

$$MR(E) = \frac{dTR(E)}{dE} = pqK\left(1 - \frac{2qE}{r}\right). \qquad (5.15)$$

The graphical picture of (5.16) is a straight, downward sloping line, as shown in figure 5.1 panel (b). Comparing this with the average revenue, $AR(E)$ in (5.10), we see that the

$MR(E)$ curve is exactly twice as steep as the $AR(E)$ curve. Putting $MR(E)$ in (5.16) equal to $MC(E)$, which is a in this case, gives the following effort level

$$E_{MEY} = \frac{r}{2q}\left(1 - \frac{a}{pqK}\right). \tag{5.16}$$

The optimal effort level, which maximises the resource rent, depends on the economic, biological and harvest efficiency parameters. E_{MEY}, where the subscript acronym means maximum economic yield, is large in the case of low effort cost and high fish price fisheries, for a given resource and harvest efficiency. The rent maximising effort level in (5.17) compared with the open-access effort in (5.11) is

$$E_{MEY} = \tfrac{1}{2} E_{\infty}. \tag{5.17}$$

Thus in the Gordon-Schaefer model the resource rent maximising effort level is just half of the open-access level. This implies that the total effort cost at the rent maximising equilibrium is just half of the open-access cost, since cost per unit of effort is constant, equal to a.

To find the resource rent maximising stock level, we commence by substituting for H from (5.5) into (5.7), which gives

$$qEX = qKE\left(1 - \frac{qE}{r}\right). \tag{5.18}$$

By substituting for E from (5.17) into (5.19) and rearranging somewhat gives

$$X_{MEY} = \frac{K}{2} + \frac{a}{2pq}. \tag{5.19}$$

Using the expressions found for X_{MSY} in (5.3) and X_{∞} in (5.15) we can rewrite (5.20) to get

$$X_{MEY} = X_{MSY} + \tfrac{1}{2} X_{\infty}. \tag{5.20}$$

The rent maximising stock level is always greater than the maximum sustainable yield stock level. In fact, we have to add half of the open-access stock level to the MSY- stock level to get the MEY level. This is due to the cost-saving effect of a large fish stock. We have seen above, in (5.15), that the open-access stock level is affected positively by the cost of effort-price of fish ratio. When this ratio is large, the MEY-stock level should also be large, to allow the cost-saving effect of the stock to compensate for the relatively large effort cost.

We have seen that the total cost is lower at the MEY equilibrium than at open access. However, in general we cannot say if the total revenue is highest for the MEY or the open-access equilibrium, as seen in figure 5.1. In fact, this depends partly on the unit cost of effort, *a*. Figure 5.1 demonstrates that the total cost curve will have a moderate slope if *a* is small, implying higher total revenue for the MEY fishery than under open access. In this case, with inexpensive harvest cost, MEY management may bring a triple dividend-reduced total cost, increased total revenue and increased stock level.

So far we have conducted the economic analysis using fishing effort as the independent variable in figure 5.1 and in several equations in this chapter. An alternative approach is to use the stock level instead of fishing effort. This has some advantages when it comes to the capital theoretic discussion on the optimal stock size. In addition, it allows a direct comparison between the open-access effort and stock levels on the one hand, and the MEY levels for effort and stock on the other hand. Even if we use the stock level as the independent variable, it has to be controlled, directly or indirectly, through harvest. At equilibrium we have $H \equiv F(X)$, which means that harvest is kept equal to the natural growth to keep the stock level constant. Thus sustainable yield equals natural growth. Combining this with a constant price of fish, p, and the natural growth function in equation (5.2), the total revenue as a function of stock size is

$$TR(X) = prX\left(1-\frac{X}{K}\right), \quad \text{when} \quad H \equiv F(X). \tag{5.21}$$

Equation (5.22) shows that the difference between the natural growth curve and the total revenue curve is to be found in the price of fish. For $p > 1$ ($p < 1$) the total revenue curve will be above (below) the natural growth curve, which equals sustainable yield.

Total cost as a function of stock size is found by multiplying the unit cost of harvesting in equation (5.13) by the sustainable yield that we used for equation (5.22). This gives

$$TC(X) = \frac{a}{qX} rX\left(1-\frac{X}{K}\right) = \frac{ar}{q}\left(1-\frac{X}{K}\right), \quad \text{when} \quad H \equiv F(X). \tag{5.22}$$

Equation (5.23) depicts a straight, downward sloping total cost curve as a function of the stock, as shown in Figure 5.2. For each stock level, $TC(X)$ tells how much it costs to harvest the sustainable yield produced at this stock level. The downward sloping $TC(X)$ curve clearly demonstrates the cost-saving effect of increasing stock size.

We can now find the resource rent as a function of stock size, $R(X)$, based on the expression found above for total revenue and total cost. The resource rent is

$$\pi(X) = prX\left(1-\frac{X}{K}\right) - \frac{ar}{q}\left(1-\frac{X}{K}\right), \tag{5.23}$$

which may be rearranged, and by substituting for X_∞ from (5.15) we have (the student should check this):

$$\pi(X) = pr(X - X_\infty)\left(1 - \frac{X}{K}\right), \quad \text{when} \quad H \equiv F(X). \tag{5.24}$$

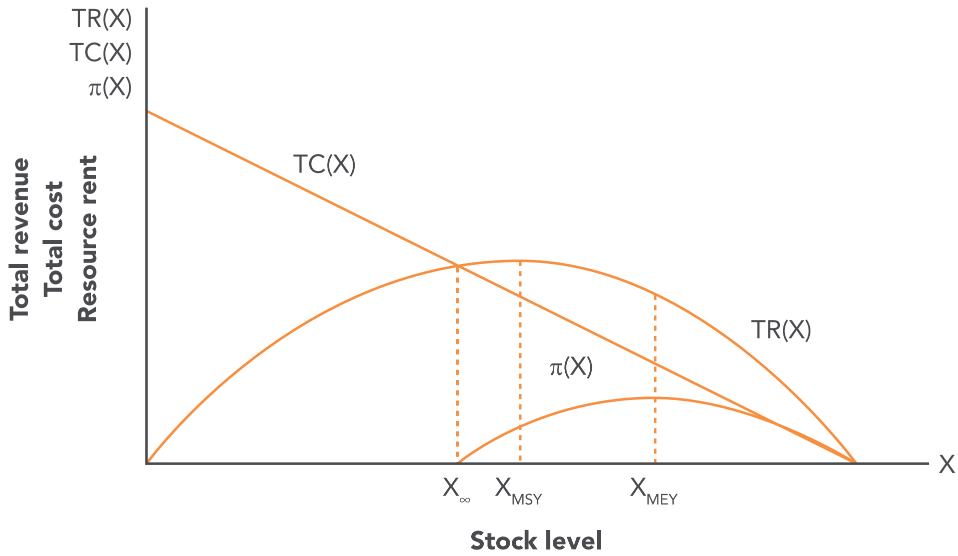


Figure 5.2. Total revenue, total cost and resource rent as functions of the stock.

We notice from equation (5.25) that the resource rent equals zero for $X = X_\infty$ and for $X = K$. Thus the open-access stock level is the lower bound and the carrying capacity is the upper bound on the stock size for a positive resource rent. The graph of the resource rent is presented in figure 5.2 together with the total revenue and total cost curves as functions of stock size. The open-access stock level, X_∞, may be below, equal to or above the maximum sustainable yield stock level, X_{MSY}, whereas the rent maximising stock level, X_{MEY}, is always above the MSY level. Figure 5.2 may be used to explain what happens to the stock level when economic parameters change. For example, if the unit cost of effort, a, decreases, the total cost curve's intersection point at the vertical axis moves downward, as seen from equation (5.23). This reduces the open access as well as the MEY stock level.

5.4 DISCOUNTING EFFECTS

In Chapter 4 we discussed the concepts of discounting and present value in relation to the capital approach to resource management. We derived, in equation (4.22), the Clark-Munroe rule that implicitly gives the optimal long-term stock level as a function of biological and economic parameters, including the discount rate. For the Gordon-Schaefer model presented in this chapter we have natural growth and cost functions that can be used to find the optimal long-run stock level. This stock level is needed to ensure the maximum present value of future resource rent, our wealth, as defined in (4.2'). To find the explicit expression for the optimal long-term stock level we commence by substituting for $F(X)$ from equation (5.2) and $c(X)$ from (5.13), in addition to $F'(X)$ and $c'(X)$, into equation (4.22). Then solve equation (4.22) with respect to X, to arrive at a quadratic equation in X (the student should check these steps). The positive solution of this quadratic equation is

$$X^* = \frac{K}{4}\left[\left(\frac{a}{pqK} + 1 - \frac{\delta}{r}\right) + \sqrt{\left(\frac{a}{pqK} + 1 - \frac{\delta}{r}\right)^2 + \frac{8a\delta}{pqKr}}\;\right] \tag{5.25}$$

To simplify somewhat we substitute the following into (5.26): $z = X/K$, $z_\infty = X_\infty/K = a/pqK$ and $\gamma = \delta/r$, and find

$$z^* = \frac{1}{4}\left[1 + z_\infty - \gamma + \sqrt{(1 + z_\infty - \gamma)^2 + 8z_\infty\gamma}\;\right]. \tag{5.26}$$

z is the normalised stock size, implying stock levels between zero and one. z_∞ is the normalised open-access stock level, and γ is the ratio of capital growth to maximum stock growth. γ could be called the bioeconomic growth rate. If $\gamma > 1$ it means that "bank" capital yields a higher interest rate than "nature" capital, and the opposite for $\gamma < 1$. We notice in equation (5.27) that the optimal long-term stock level, on its normalised form, depends on just two variables, the normalised open-access stock level, z_∞, and the bioeconomic growth rate, γ. Table 5.1 shows how z^* varies with z_∞ and γ. For zero discount rate the optimal stock level, according to equation (5.27), is $z^* = ½ + z_\infty/2$. Comparing this with the expression for X_{MEY} in equation (5.21) we infer that $X^* = X_{\text{MEY}}$ when $\gamma = \delta = 0$, since $z_{\text{MSY}} = ½$. Thus, when the discount rate goes to zero, the optimal long-term stock level goes to the resource rent maximising level. In fact, we have previously seen this through the graphical analysis in Figure 4.2. We also notice from equation (5.27) that the optimal stock level equals the MSY level only for zero effort cost and zero discounting. In this case $z^* = z_{\text{MSY}} = 1/2$, since $z_\infty = 0$ and $\gamma = 0$.

γ \ z_∞	0	0.10	0.30	0.50	0.70	0.90
0	0.50	0.55	0.65	0.75	0.85	0.95
0.10	0.45	0.51	0.62	0.73	0.84	0.95
0.25	0.38	0.45	0.59	0.71	0.83	0.94
0.50	0.25	0.37	0.54	0.68	0.81	0.94
1.00	0	0.25	0.47	0.64	0.79	0.93
2.00	0	0.16	0.40	0.59	0.77	0.92
5.00	0	0.12	0.34	0.54	0.73	0.91
∞	0	0.10	0.30	0.50	0.70	0.90

Table 5.1. Optimal normalised stock level as a function of the open-access stock level, z_∞, and the bioeconomic growth rate, γ.

From Table 5.1 we see that if the bioeconomic growth rate goes to infinity, $\gamma = \delta / r \rightarrow \infty$, the optimal stock level equals the open-access level, since the values in the last row equal the z_∞-values in the head row. Generally, the optimal stock level decreases with the bioeconomic growth rate – that is, when we move down a given column in Table 5.1. Also notice that the effect of the discount rate on the optimal stock size is greater for low-cost fisheries than for high-cost fisheries. In Table 5.1 low-cost fisheries are found in the columns to the left, recalling that $z_\infty = a/pqK$. "Low-cost" in this connection could also mean high-valued and easy-to-catch since p and q appear in the denominator and a in the numerator of z_∞.

Table 5.1 demonstrates, in the column of $z_\infty = 0$, that, with costless harvesting, the stock owner may want to extinguish the stock when the bioeconomic growth rate is equal to or greater than one. When $\delta = r$ ($\gamma > 1$) the fish has higher value in the "bank", at a discount rate of δ, than in the sea, at a maximum growth rate of r. In this case, with zero harvest cost, the resource owner would want to transform his capital from "fish in the sea" to "money in the bank" to maximise his wealth. In actual fisheries, however, effort costs are not zero and harvest efficiency, expressed by q, is not infinitely high. Thus the analysis of the effects of an infinitely high discount rate may be seen mainly as a modelling exercise, and not as a prediction of what would happen if a natural resource is managed by a sole owner. On the other hand, if biological, economic and harvest technical conditions are such that open-access harvesting would imply extinction of the resource, transferring the resource to a sole owner would not necessarily be sufficient to save the resource from extinction.

Exercise 5.1.

A fish stock X has the following natural growth function

$$F(X) = rX\left(1 - \frac{X}{K}\right) \tag{1.1}$$

Assume that *F(X)* is the annual natural growth when the size of the stock at the beginning of the year is X.

1. Draw the graph based on (1.1) when r = 0.30 and K = 8000. K is measured in thousand tonnes.
2. What unit of measure does r have? Discuss the biological parameters r and K using the graph in question 1.
3. Assume that no fishing takes place. What is the equilibrium size of the fish stock, according to equation (1.1)?

We introduce the following harvest function

$$H(E,X) = qEX, \tag{1.2}$$

where q is the catchability/availability parameter/coefficient and E is fishing effort.

4. Discuss the catchability parameter q.

With harvest, H, change in the stock level per unit of time is

$$\dot{X} = F(X) - H(E,X) \tag{1.3}$$

5. Define equilibrium fishing, using function (1.3), and show that the equilibrium harvest, H, can be presented as a function of X. Compare this function with function (1.1). What characterises equilibrium fishing?
6. Find an expression for the stock level (X_{MSY}) that gives maximum sustainable yield H_{MSY}

   (Hint: $\frac{dH}{dX} = 0$ is a necessary condition).

7. What is the size of X_{MSY} and H_{MSY}, in thousand tonnes and thousand tonnes per year, respectively?
8. Assume that no fishing has taken place and the fish stock is at its pristine/virgin equilibrium. What is the size of the harvest in year 1 when fishing effort is E = 100, and $q = 0.001\frac{1}{vessels \cdot year}$?
9. Explain why the harvest in year 1 (see question 8) is higher than the maximum sustainable harvest/yield you found in question 7.
10. Use equations (1.1), (1.2) and (1.3) to find the equilibrium harvest H as a function of effort E (Hint: from (1.2) follows $X=H/qE$).
11. What is the equilibrium harvest when fishing effort is kept constant at 100 vessels per year?

12. What is the equation for annual total revenue as a function of effort, *TR(E)*, (for equilibrium harvesting) when the price of fish is constant?
13. What is the expression for sustainable resource rent when total fishery is

$$TC(E) = aE \tag{1.4}$$

14. The economic parameters are p = 1.0 \$/kg and a = 1.0 million \$/(vessel × year). What is the size of the equilibrium fish stock in an Open Access fishery? What is the total harvest in this case, and how many vessels participate?
15. What are the optimal/*MEY* fishing effort and the corresponding stock level and harvest? What is the maximum annual resource rent (total and per vessel)?

Exercise 5.2

1. Show that for the Schaefer model the long-run optimal stock level X^* is as given in equation (5.26).
2. Use the parameters from a previous exercise and δ = 10% to find the value of X^*.
3. Compare X* to what you previously found for X_{oo} and X_{MEY} and discuss the differences.

Exercise 5.3

Assume that the function

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

describes the growth of the fish stock. X represents the stock biomass, K is the environmental carrying capacity and r is the intrinsic growth rate.

Further we assume that the harvest function is linear in effort (E) and stock level.

$$H = qEX$$

where q s a constant catchability coefficient, and E is the total effort (measured in number of vessel year).

a) Show that the equilibrium harvest function will be:

$$H(E) = qKE\left(1 - \frac{qE}{r}\right)$$

b) Draw a picture of $H(E)$ for the values $r = 0.4$, $K = 8000$ (million tonnes) and $q = 0.001$.

c) Find the level of effort that gives maximum sustainable yield (E_{MSY}), and the sustainable yield for this level of effort (H_{MSY}).

Assume a constant price of fish (per unit of weight), p, and a constant cost per unit of effort, a.

d) Calculate the equilibrium effort and harvest in the case of open access (E_∞ and H_∞), when the price and cost values are $p = 10$ and $a = 20$ (and the parameter values from b)).

e) Calculate the equilibrium effort and harvest in the case of optimal economically solution (E_{MEY}) and H_{MEY}) (with the same price, cost and parameter values).

f) Assume that the government introduces a fixed tax per unit of effort. Which value of this tax should be chosen to reach the optimal solution?

6 FISHING VESSEL ECONOMICS

In this chapter we apply microeconomic theory to the operation of fish harvesting firms, including analysis of small-scale fishers' decision-making and the effects of share arrangements. Stock size and its availability for fishing are exogenous variables for each firm.

6.1 OPTIMAL VESSEL EFFORT

In the previous chapters we assumed that vessels are homogenous with respect to cost and catchability, implying that cost per unit of effort, a, is constant and equal for all vessels. The reason for this is the long-run perspective where it is reasonable to assume that adding homogenous vessels to the fleet can expand effort at a constant cost per unit effort. In actual fisheries vessels usually differ with respect to efficiency and costs. The latter is also the case for the opportunity cost of labour which may vary across geographical areas. For example, fishers living in a small coastal community far away from larger towns and cities usually have few alternative employment possibilities; thus the opportunity cost of labour will be lower in such a community than in larger labour markets. On the other hand, other inputs required for fishing may be more costly in small fishing communities than in towns, due to transportation cost and less competition between distributors. The price of fuel, for instance, seems to be higher in small, remote fishing communities than in larger towns. Thus, differences in efficiency of effort, market prices of inputs and opportunity cost of labour may all contribute to the existence of heterogeneous effort in the fish harvesting industry.

Before analysing the bioeconomic effects of heterogeneous effort (see chapter 7) we shall in this chapter study the **economic adaptation** of fishing vessels. This includes the **economic objectives** of fishing activities, the costs structure and the size and availability of the natural resource, the fish stock. The activity level of a vessel is measured by its fishing effort, and we reckon that any vessel's effort can be expressed by use of a standardised efficiency measure of fishing effort. The unit of measurement of effort at the vessel level, e, could be, for example, one hour of trawling in demersal trawl fisheries, one gill net day in coastal gill net fishing or 100 hooks in long line fisheries. Vessel effort, e, is in technical terms and it takes labour, fuel, gear etc. to produce effort. This may be expressed in the production function $e=f(v_1,v_2,\ldots v_n)$ at the vessel level, where the v's are the inputs. Recall the fishery wide effort function with total effort, E, in equation (2.2). Total effort is the aggregate of the effort of all vessels in a fishery. This production function has the same characteristics as we are used to in the theory of the firm in a microeconomic text. It may have one, two or n number of inputs and it may have constant returns to scale or variable returns to scale (see Varian, 2003).

We use the following symbols to analyse a vessel's economic adaptation of fishing effort

e = effort of one fishing vessel
$c(e)$ = total variable cost of effort
$avc(e)$ = average variable cost of effort
$mc(e)$ = marginal cost of vessel effort

Sometimes, subscripts i and j will be used to distinguish between or to compare two vessels. At this stage we disregard fixed cost, but shall return to this when discussing long-run issues in section 6.2.

Average variable cost of vessel effort equals total variable cost divided by effort:

$$avc = avc(e) = c(e)/e.$$

Marginal cost of vessel effort is the addition to total cost due to the addition of one unit to effort:

$$mc = mc(e) = d\, c(e)/d\, e.$$

If effort is measured in trawl hours, the average variable cost tells how many $ one hour of trawling on average costs, whereas marginal cost tells by how many $ total cost increases with the addition of one hour of trawling.

Each vessel can vary effort by varying the inputs needed for the generation of effort. For example, in the case of trawling, a vessel can vary its speed between harbour and fishing ground, allowing more or less time for proper harvest activities on the fishing ground. High speed to and from the fishing ground means more time for actual fishing. Since engine fuel consumption increases progressively with speed, this implies that also marginal cost of vessel effort increases with expansion of effort.

Recalling the theory of the firm, marginal cost may decline with output at low level, reaches a minimum, and rises thereafter, due to the form of the production function. In the case of fisheries we may think of effort as the (intermediate) product of the production process and that this (intermediate) product is produced by regular inputs according to a regular production function.

When the catch of a vessel is small in relation to the stock size, the vessel operator considers stock as constant in the short-run, not affected by the activity of the vessel. This also applies to the market price of fish – seen from a vessel operator's point of view, the market price is considered unaffected by the landings of each vessel. Even if there are effects on stock and market price from the total harvest of all vessels, the magnitude of this is an empirical question. However, for the analysis of a single vessel's adaptation we shall assume that there are no significant effects on stock level and market price. Thus, the vessel operator acts as if his fishing has no effect on the stock level or on the market price.

In a given period of time the vessel's catch is a function of its effort, which it can adapt, and the stock level, which is taken as given. For the case of simplicity, let us assume that the vessel harvest function equals the Schaefer harvest function:

$$h(e;X) = qeX \,, \tag{6.1}$$

where q is the catchability coefficient.

The operating profit of the vessel is

$$\pi(e;X) = p \cdot h(e;X) - c(e) \tag{6.2}$$

Using (6.1) and (6.2) the operating profit is

$$\pi(e;X) = p \cdot qeX - c(e) \tag{6.3}$$

We have included the stock level as an argument in functions (6.1) and (6.2), but after the semicolon of the functional symbols to stress that the stock level has an effect on harvest and that this is outside the control of the vessel operator. However, to simplify the notation, this has not been done for the fish price.

Assuming that the vessel operator maximises operating profit given in equation (6.3), the first order condition for this is

$$\pi'(e;X) = pqX - mc(e) = 0 \tag{6.4}$$

Equation (6.4) implies the following criterion for the vessel's adaptation of its effort

$$mc(e) = pqX\,. \tag{6.5}$$

Equation (6.5) tells that the marginal cost of vessel effort shall equal the marginal revenue of effort. The latter equals the product of fish price, catchability coefficient and stock level, and this product is the revenue earned by the addition of one unit of effort. Note that in the traditional theory of production, or theory of the firm, the right- hand side of the equation, corresponding to (6.5), would include only p, whereas in this case both q and X are included in addition to the price. For a given set of p, q and X, the vessel's **optimal effort** is implicitly given by equation (6.5).

In studying the theory of production, we usually measure product along the horizontal axis whereas in this case we have used fishing effort as the fisher's decision variable. The reason for this is discussed above. An ordinary firm is considered to have control of its total production process, including all inputs needed and the costs of these. A fish-harvesting firm, however, does not have control of its most important input, the fish stock. This is definitely not an input like fuel and bait that can be bought in the input market. The fisher knows the cost per unit of effort, for instance, per trawl hour, and we anticipate that he also knows how the catch varies with stock level. Thus cost per unit of harvest will depend on both input costs and on the stock level and its catchability.

The average variable cost and the marginal cost curves are shown in figure 6.1. Panel (a) of this figure shows that *avc* first declines, reaches its minimum for effort level e_∞, and rises thereafter. The *mc* curve first declines, reaches its minimum for an effort level lower than e_∞, and rises thereafter. When the *avc* curve attains its minimum, *mc* equals *avc*. We recognise the form of these cost curves from the theory of the firm, with the important difference that in this case effort is the variable along the horizontal axis, whereas the corresponding variable in the theory of the firm is the firm's quantity of output. We may regard vessel effort as an intermediate output of the fish-harvesting firm – an output produced by use of regular inputs. However, how

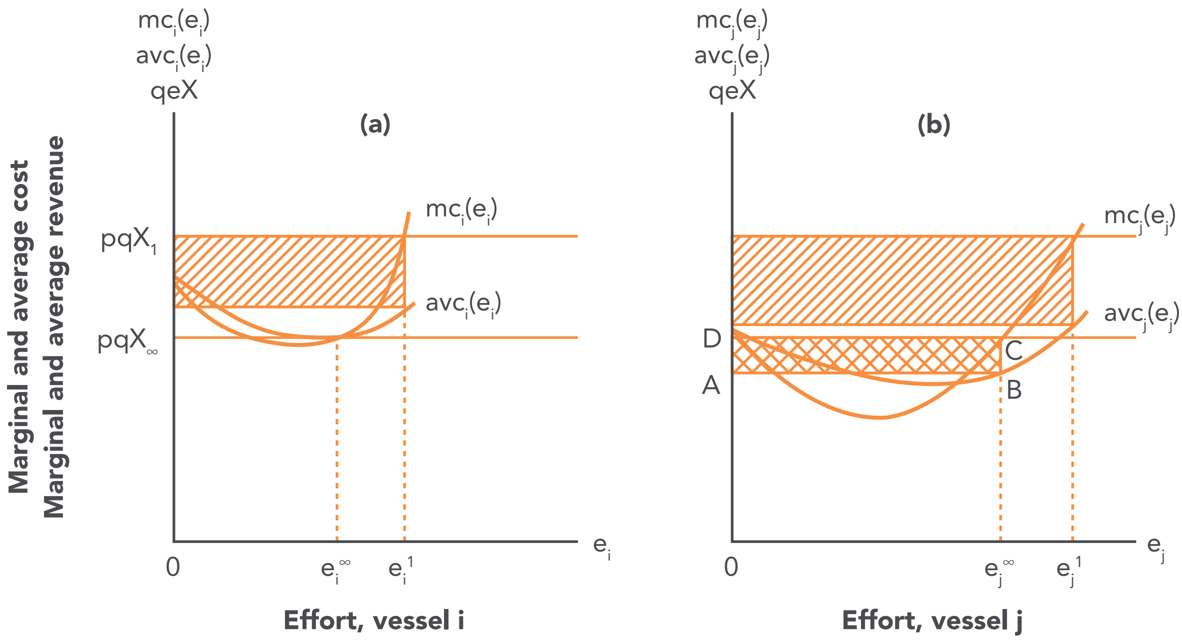


Figure 6.1. Two fishing vessels: short-run adaptation of effort for given cost structure, price of fish, catchability and stock level.

much of the final output, fish catch, the effort produces depends on the stock size and its availability, in addition to the effort. Once we know how much catch is produced by effort, cost per unit of harvest can also be calculated. (In chapter 3.1 we introduced the cost per unit of effort, a, and in chapter 4.2 the unit cost of harvest was introduced.) The distinction between (average and marginal) cost per unit of effort on the one hand and cost per unit of harvest on the other hand is crucial for the understanding of fisheries economics.

Figure 6.1 shows graphically the adaptation of effort for two profit maximising vessels, vessel i and vessel j. Panel (a) of this figure shows the marginal revenue of effort, pqX, for two levels of the fish stock, namely X_∞ and X_1. The optimal effort of vessel i is e_i^∞ for stock level X_∞. This effort is according to the optimality criterion in equation (6.5), that is, marginal cost of effort equals marginal revenue of effort. In this case vessel i does not make any profit, but just breaks even, since the marginal revenue of effort, pqX_∞, equals average variable cost. If the stock level is lower than X_∞ it will be optimal for this vessel to stop fishing since marginal revenue will be below the minimum average cost. In this case, without any fixed cost, it is better for the vessel to be idle with zero revenue and zero cost, than to operate with a negative result. Vessel i is a marginal vessel for stock level X_∞ since just a small reduction in the stock level will force the vessel out of operation.

Figure 6.1 panel (b) shows that vessel j has its maximal profit for effort e_j^∞ at stock level X_∞, and that profit equals the area ABCD in this case. This profit is called producer's surplus or quasi-rent in the theory of the firm and intra-marginal rent in fisheries economic theory.[10] The latter refers to rent earned by those vessels that are more cost efficient than the marginal vessel. In figure 6.1 vessel i is a marginal vessel at stock level X_∞ whereas vessel j is intra-marginal at this level. Note that vessel j would be able to operate with a positive profit even at a stock level somewhat lower than X_∞.

If the stock level is X_1, instead of X_∞, by chance or by active management of the fishery, figure 6.1 shows that the profit maximising effort will be e_i^1 and e_j^1, for vessel i and j, respectively. In this case the profit for each of these two vessels will equal the single-shaded areas of panel (a) and panel (b). In other words, higher stock level means higher marginal revenue of effort, thus encouraging each vessel to increase its effort. How much vessel effort increases depends on the steepness of the marginal cost curve. If this curve is very steep the optimal effort will hardly be expanded if stock level increases, as is the case at stock level X_1 for vessel i in figure 6.1 panel (a).

6.2 VESSEL BEHAVIOUR IN THE LONG RUN

Up to this point we have not been specific about short run versus long run. Like any firm, a fish harvester may have different criteria for its short-run and its long-run adaptation.[11] In the short run it suffices to cover operation cost whereas in the long run a harvester will have to cover his fixed cost as well. This is illustrated in figure 6.2, where marginal and average cost curves are based on the total cost $tc(e) = c(e) + k$, with $c(e)$ as variable cost and k as fixed cost. Marginal effort cost is $mc(e)$, average variable cost of effort is $avc(e)$ and average total cost of effort is $atc(e)$.

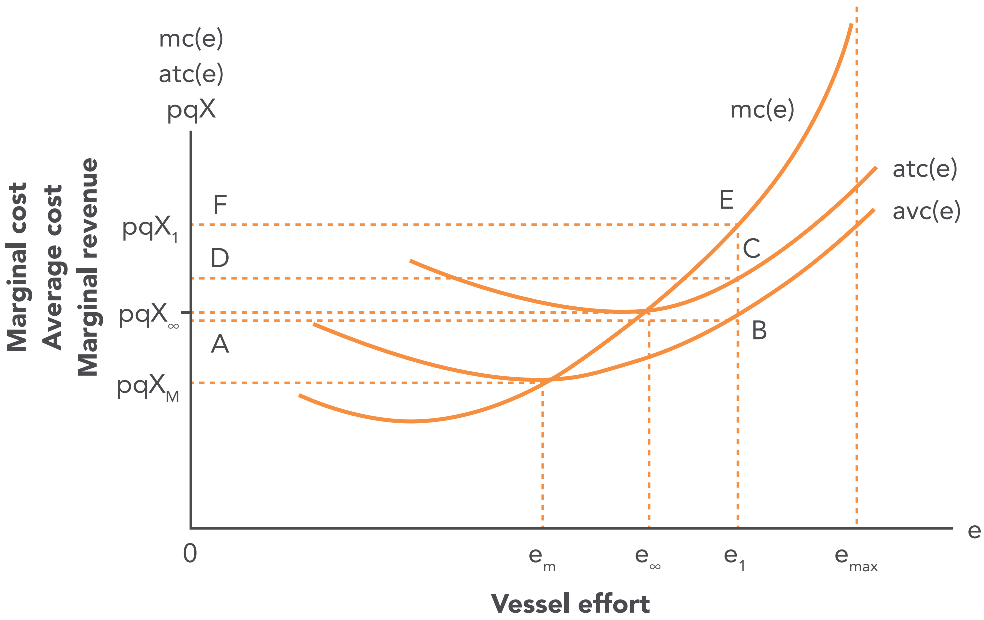


Figure 6.2. Short-run and long-run adaptation of fishing effort may differ due to fixed costs.

Note that the marginal cost of effort curve intersects from below the two average cost curves at their minimum points. For obvious reasons the average total cost curve lies above the average variable cost curve at any effort level. However, the difference between average total cost and average variable cost narrows when effort expands since this allows the fixed cost to be divided by more units of effort. In the short run a vessel may operate if marginal revenue of effort is above pqX_M, which is equal to the minimum of its average variable cost. For given values of p and q this implies that the stock level at least has to be above X_M for fishing operations to take place on a commercial basis. In figure 6.2 X_1 is greater than X_∞, which is greater than X_M. In the long run a vessel will also have to cover fixed costs, which implies that the stock level has to be at or above X_∞ for the vessel to be able to cover its capital cost. We have used subscript ∞ to indicate that this is the stock level at which the marginal vessel breaks even under an open-access fishing regime. The marginal vessel, producing effort e_∞, will be able to cover all its costs, including normal capital return, but without earning any above normal profit. However, if effective management measures have been taken and the stock level is kept at, for example, X_1, the vessel will earn the gross profit ABEF shown in figure 6.2. This gross profit includes the super profit DCEF. In this case the super profit is the vessel's share of the resource rent.

The optimal vessel effort depends on the marginal revenue, denoted *pqX* in figure 6.2, and on the marginal cost of effort curve. For a constant price of fish and a constant catchability parameter this implies that the marginal cost curve represents the vessel's supply curve for fishing effort. If the product of price, catchability and stock level, *pqX*, increases, the vessel's optimal effort will increase. For example, if a gill-net vessel experiences higher marginal revenue of effort, it could increase its profit by increasing its use of variable inputs, such as fuel necessary to increase the speed between the harbour and the fishing ground. A vessel has greater flexibility in varying its effort the gentler the marginal cost curve. Traditionally, in many parts of the world, fishing vessels have been designed and manned to be flexible to adapt to changing markets and resources. This means, in the context of figure 6.2, a moderate sloping marginal cost of effort curve.

6.3 QUOTA PRICE AND OPTIMAL EFFORT

We shall now analyse how the optimal vessel effort and harvest depend on the harvest quota price. In Chapter 3.4 we analysed the market price of effort quotas and harvest quotas by use of downward sloping demand curves. Having seen above how the marginal cost of effort becomes the vessel's supply curve for fishing effort, we shall now have a closer look at the relationship between this supply curve and the demand of effort and harvest quotas. In particular we shall see how the market price of fish, harvest costs, technological efficiency and stock level affect a fishing firm's demand for harvest quotas. Let us assume that fish harvesters can buy any amount of harvest quota at the price of *m* $ per tonne. The quota price may be given either in a competitive market or as a harvest tax determined by a fishery manager. Disregarding uncertainty, a profit maximising firm will adapt fishing effort and harvest as discussed above, but with the additional constraint that it has to pay for its quota in proportion to its harvest.

To simplify the graphical analysis we assume a linear marginal cost of effort curve, shown in figure 6.3 panel (a).[12] Based on this we shall derive the downward sloping demand curve for harvest quota in panel (c). In figure 6.3 panel (a), fishing effort is measured horizontally and marginal cost of effort, average total cost of effort and marginal revenue of effort are measured vertically. Since the fishing firm has to pay for its harvest quota, its net price of fish is $p - m$, and it is this net price that matters for the vessel's adaptation of effort. If the landing price of fish is 2.00 €/kg and the market price of quota is 0.75 €/kg, the net price of fish for the vessel equals 1.25 €/kg. When harvest quotas are for free ($m = 0$), the optimal level of vessel effort, e^0, is formed, in figure 6.3 panel (a), where the marginal cost of effort curve intersects the horizontal marginal revenue line at level pqX. Note that pqX is assumed to be constant throughout this analysis, whereas we discussed effects of changes in the stock level in figures 6.1 and 6.2. Figure 6.3 panel (b) shows the optimal effort as a function of the harvest quota price, including e^0 for the zero harvest quota price. Panel (c) shows the vessel's demand for harvest quota as a function of quota price. This is derived from panel (b) using the harvest function $h = qeX$. Catch h follows in a straightforward way when e has been derived, since, by assumption, qX is constant.

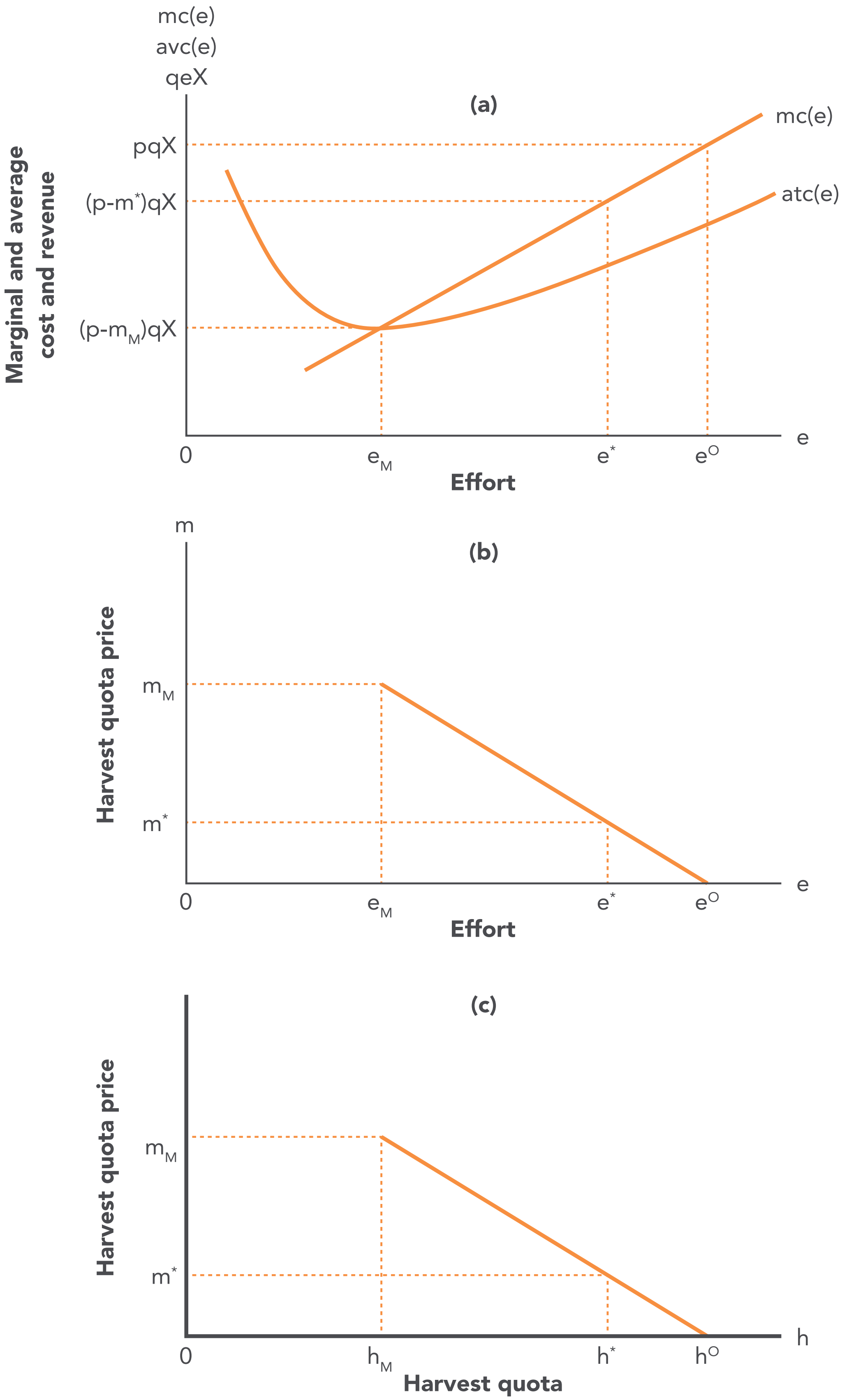


Figure 6.3 A vessel's demand for harvest quota depends on its cost structure, price of fish, catchability and stock level.

In the same way as the optimal effort and the harvest quota were derived for the zero quota price, they can be derived for any quota price, including m^*. As noted above, in this case it is the net price of fish, $p - m^*$, that matters for the fishing firm. The harvest quota price m_M is the maximum price the vessel portrayed in figure 6.3 can afford to pay without losing money in the long run. If the harvest quota price is greater than m_M, the horizontal marginal revenue line will be below the maximum of the average total cost of effort curve. Thus in such a case the optimal vessel strategy is to stop fishing to avoid losing money through a negative net profit. In the short run, however, a vessel with an effort cost structure similar to what is shown in figure 6.3 panel (a) can operate for a while and earn a positive gross profit even if the harvest quota price is greater than m_M.[13] The combination of positive gross profit and negative net profit is most likely to appear for vessels with high fixed costs. This would imply a greater difference between average total cost and average variable cost, and a gradual phasing out of bankrupt vessels not able to meet their log-run capital obligations. On the other hand, capital-intensive vessels may be more efficient than other vessels, thus compensating for higher fixed costs with lower variable costs. To predict what kind of vessels would be most competitive in a quota market, one would need empirical information about fishing firm and vessel costs.

6.4 A SMALL-SCALE FISHER'S CHOICE OF LEISURE TIME AND INCOME

We have seen above how a fish harvesting firm adapts effort to maximise profit. The effort supply curve is typically upward sloping, implying that a vessel is used more intensively the higher the marginal revenue of effort. However empirical studies of small-scale fisheries in some cases seem to contradict this result, showing that effort may even decrease with increased marginal revenue of effort. Sociologists and anthropologists have attributed this to fishers' and their families' social and economic needs, which may differ between different people (see e.g. Maurstad, 2000). In economics we recognise differences in individual preferences, in particular in the theory of the consumer. Some people prefer to buy more apples than pears and some prefer to work part time instead of full time. Let us now use and adapt the theory of consumer behaviour to analyse how a small-scale fisher may chose to allocate his total available time between fishing – to earn income to buy consumer goods – and leisure time. In other words this is to analyse the choice between income and leisure. Since income – or consumer goods – and leisure are alternative sources of utility, an indifference map may represent the fisher's preference pattern between them, for example, such as one of the two shown in figure 6.4.

The following symbols are used

x = quantity of consumer goods
P = consumer price index
T = time constraint (total hours available)
e = fishing effort, in hours of fishing
z = hours of leisure time
w = income per hour of fishing

The fisher's utility is a function of consumer goods and leisure time

$$U = U(x,z)\,. \tag{6.10}$$

The time constraint of the fisher is

$$T = e + z\,. \tag{6.11}$$

The fisher's budget constraint is

$$wT = Px + wz\,, \tag{6.12}$$

since wT is the maximum income he could earn if he spent all his available hours on fishing. This is distributed across leisure time, wz, and consumer goods, Px. Thus the actual income from fishing is $we = wT - wz$. The small scale fisherman wants to maximize his utility, we assume, by choosing x and z. This means we should find the maximum of the utility function (6.10) given the budget constraint (6.12). This can be done by one of two methods. First, by substituting for x from equation (6.12) into (6.10), which makes utility a function of only one variable, z, and maximizing utility with respect to this variable, leisure time. Second, we can use the Lagrange method (see Box 6.1). The two methods lead to the same result that the necessary condition for the fisher's optimal adaptation is

$$\frac{U_z}{w} = \frac{U_x}{P}\,, \tag{6.13}$$

where

$$U_x = \frac{\partial U(x,z)}{\partial x} \text{ and } U_z = \frac{\partial U(x,z)}{\partial z}.$$

Dear student, you should now do the calculations that lead to equation (6.13).

The interpretation of equation (6.13) is that the marginal value of one dollar from fishing should be the same whether spent on leisure time or on consumer goods. In other words, at the margin the fisher is indifferent between a small increase in consumer goods or in leisure time.

The budget constraint may be rewritten

$$z = T - (P/w)x \tag{6.14}$$

to see that it is only the real value of income per hour of fishing that counts for the fisher.

Box 6.1 Using the Lagrange method

This method uses an assisting function, which combines the function we are going to maximize (utility) and the constraining function (budget), and has got its name after the French mathematician and astronomer *Joseph Louis Lagrange (1736–1813).*

Maximizing the utility, $U = U(x,z)$, subject to the linear constraint, $wT = Px + wz$, we start by introducing a helping hand, the Langrangian multiplier λ, and formulate the Langrangian function

$$L = U(x,z) - \lambda(Px + wz - wT).$$

Note that what is in the parenthesis following λ equals zero. Thus maximizing the L-function will give the same result as maximising the U-function, but now we can be sure that the budget constraint is fulfilled.

The Langrangian theorem states that an optimal choice of (*x,z*) must satisfy the following three equations, the first order conditions,

$$\frac{\partial L}{\partial x} = U_x - \lambda P = 0 \qquad \text{(B6.1)}$$

$$\frac{\partial L}{\partial z} = U_z - \lambda w = 0 \qquad \text{(B6.2)}$$

$$\frac{\partial L}{\partial \lambda} = Px + wz - wT = 0 \qquad \text{(B6.3)}$$

Using the first two of these equations we arrive at the condition

$\frac{U_z}{w} = \frac{U_x}{P}$, which is the same as in equation (6.13).

The three equations (B6.1)–(B6.3) can be used to find the three unknown variables x, z and λ. However, to find explicit solutions we would have to specify the utility function. In microeconomic texts you may find several examples of utility functions, such as the Cobb-Douglas function and the linear function.

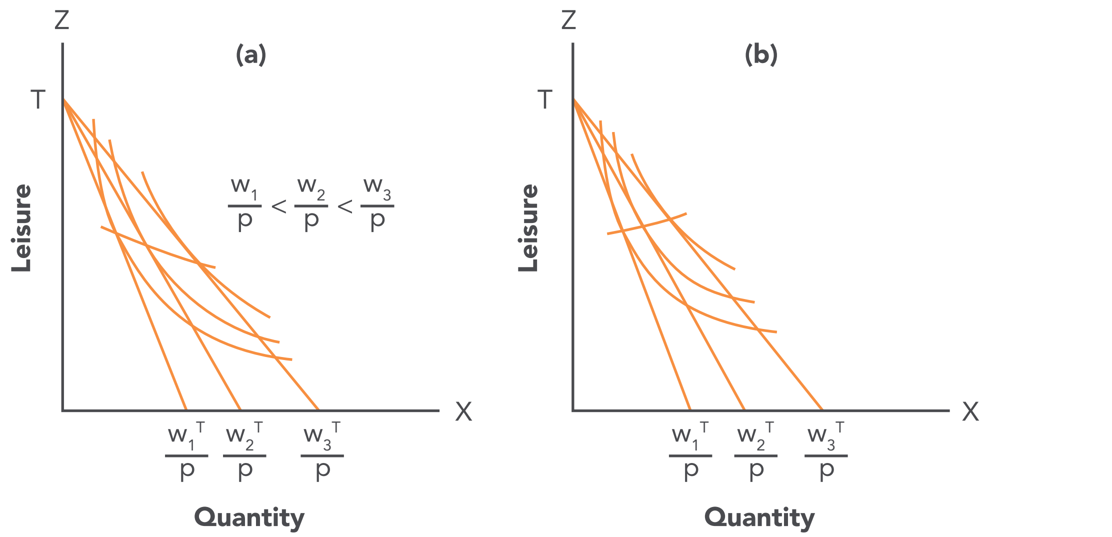


Figure 6.4 Two examples of the small-scale fisher's choice between consumer goods and leisure time.

Let us now analyse what happens to the fisherman's choice between leisure time and consumer goods if fishing conditions improve. The preference map in Figure 6.4 panel (a) is such that the fisherman would like to reduce his leisure time if real value of income per hour increases from $\frac{w_1}{P}$ to $\frac{w_2}{P}$, and further to $\frac{w_3}{P}$. This implies that he increases his fishing time and the consumption of goods. In this case the fisher's labour supply curve – measured by his fishing time – is upward sloping. Figure 6.4 panel (b) shows the preference map of a fisher who will increase his leisure time when real value of income per hour of fishing increases. This fisher will decrease time allocated to fishing if the real value of his hourly income increases, in other words, his supply curve for labour is downward sloping.

Figure 6.5 shows two possible supply curves for fishing effort for a small-scale fisher who allocates his time between leisure and fishing – the latter to earn income to buy consumer goods. Thus, based on this theory we cannot tell whether a small-scale fisher will increase or decrease his fishing effort when the real value of his hourly income increases. This real value of hourly income is the fisher's opportunity cost of effort. Note the difference between this inconclusive result regarding the slope of a small-scale fisher's effort supply curve and the fishing firm's upward sloping effort supply curve derived in the previous section. This difference may also have implications for the design of management tools. It is not certain that the same management instruments will work efficiently for both industrial (large-scale) fisheries and for small-scale fisheries.

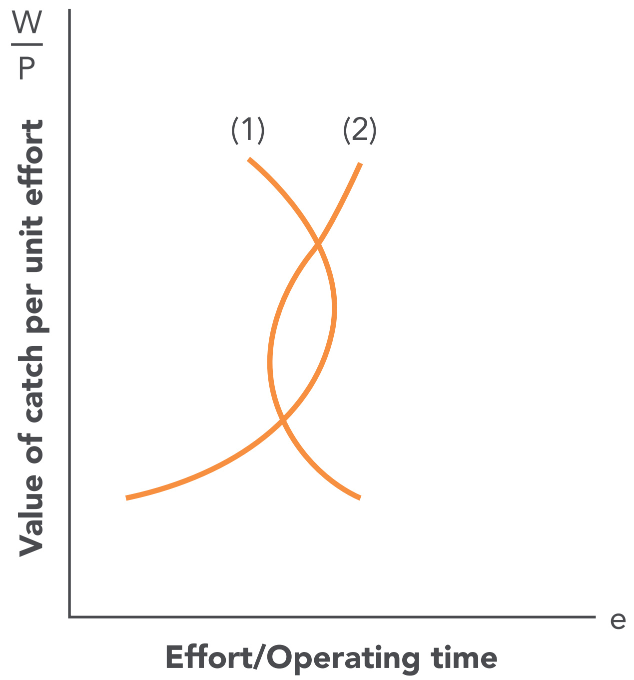


Figure 6.5. The effort supply curve in small-scale fisheries may be backward or forward bending, depending on the fisher's preferences for leisure time and consumer goods.

Exercise 6.1

A fishing vessel has harvest function $h = qeX$ (with q and X exogeneously given), price of fish p, fixed cost k, variable cost $vc(e) = ce + ae^2$ and unit cost of harvest quota m.

1. What is the optimal effort, expressed as a function of other variables and parameters?
2. What is the optimal harvest, expressed as a function of other variables and parameters?
3. What is the harvest quota demand function (inverse; m as a function of h)?
4. Draw a picture of what you found in question 3 for the following parameter values:

Symbol	Value	Unit
p	3000	€/tonne
m	min: 0 max: 1000	€/tonne
c	60	€/hour
a	0.045	€/hour^2
k	259 200	€/year
q	1.2×10^{-6}	1/hour
X	10^5	tonne
vc	-	€/year
tc	-	€/year

5. Draw a picture of marginal revenue of effort ($(p - m)qX$), marginal cost, average variable cost and average total cost as functions of effort, using data from question 4. What is the optimal vessel effort for $m = 0$ and $m = 1000$? For what effort level does the average total cost have its minimum?

Exercise 6.2

A fishing vessel has harvest function: $h = q\, e\, X$ (with q and X exogenously given). The vessel has the following total cost function:

$$tc(e) = \frac{1}{3}e^3 - 50e^2 + 2530e + 81000$$

a) Find the expression for: $mc(e)$, $avc(e)$ and $atc(e)$ (marginal cost, average variable cost and average total cost).

b) Assume that the marginal revenue (mr) of effort is

$$mr = pqX = 2055$$

What is the optimal effort?

c) Suppose that stock and/or price reductions give another mr:

i) $mr = 1255$

ii) $mr = 655$

What is the optimal effort in these cases?

d) Draw a picture.

7 EXTENSION OF THE BASIC BIOECONOMIC MODEL

This chapter demonstrates that even in an open-access fishery rent may be generated if vessels are heterogeneous. An empirical example from Vietnam is given. Further, we extend the bioeconomic model to include areal distribution and migration of fish, on the background that marine reserves are established in many countries. The analysis includes achievements with a reserve and open-access harvesting outside with respect to stock protection, sustainable harvest, employment and rent.

7.1 INTRA-MARGINAL RENT FOR THE MOST EFFICIENT VESSELS

In this section we will study some management issues related to a fishing fleet of heterogeneous vessels. In most fisheries vessels vary with respect to size, engine power, gear-type, costs and other technical and economic characteristics. In the preceding chapter we have seen examples of how the cost structure of vessels may differ. However, when, in Chapters 3 and 4, we discussed open-access and managed fisheries, this was done for homogeneous vessels. The reason for this is the wish to start with the simplest model that may provide insight in the economics of fishing. From this we learned that the potential resource rent is wasted in an open-access fishery, but that sole ownership or other management measures can mitigate this and create resource rent. Now, what are the results when there are technically and economically heterogeneous vessels?

Figure 7.1 shows for each of twelve vessels the standardised effort along the horizontal axis and the average cost per unit of standardised effort along the vertical axis. The vessels are arranged from the left to the right according to their cost efficiency, with vessel no. 1 as the most cost efficient one and vessel no. 12 as the least cost efficient. We may choose, for example, vessel no. 9 as the standard vessel against which the efforts of the others are measured. Since the width of each vessel bar in Figure 7.1 illustrates the standardised effort of each vessel, we notice that, for example, vessel no. 3 produces about twice as much effort as the standard vessel, no. 9. This implies that vessel no. 3 would catch twice as much fish per day as vessel no. 9, when effort is measured in hours or days of fishing of the standard vessel. Further, we notice in Figure 7.1 that the average cost per unit of standardised effort is lowest for vessel no. 1, even though this vessel no. 1 produces the same effort as the standard vessel no. 9.

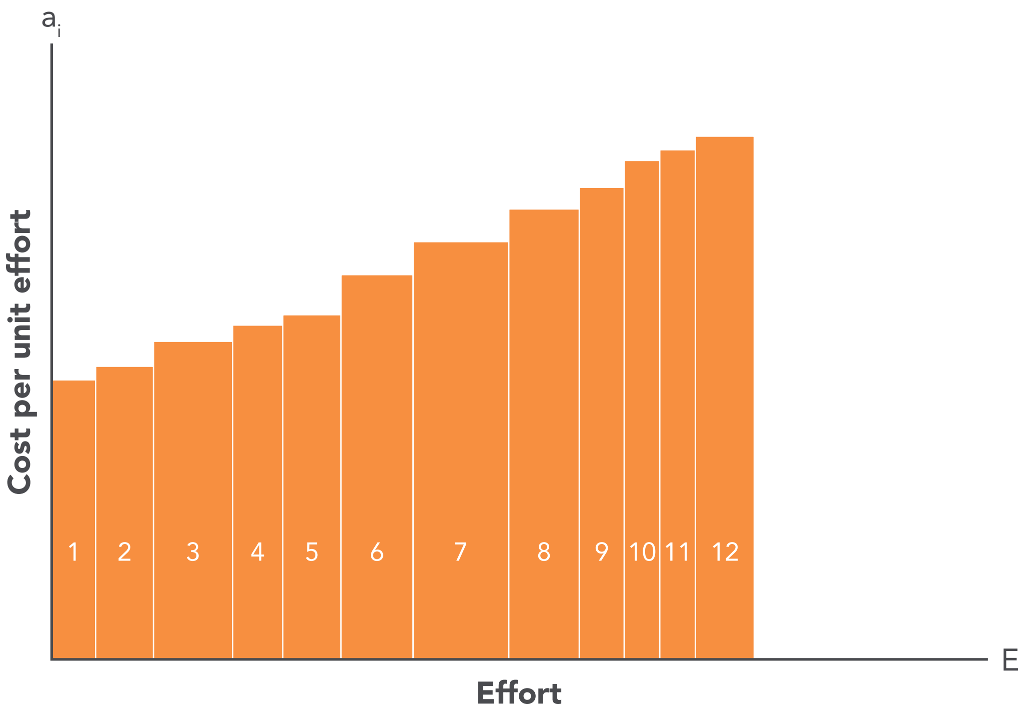


Figure 7.1. The increasing marginal cost of effort curve for a fishery is based on heterogeneous vessels. The fishing effort of each vessel is measured by the width of the bar whereas the height of the bar measures cost per unit of effort.

With several vessels in a fishery, we may substitute the cost bars in Figure 7.1 with a curve enveloping the bars. This curve is called the $MC(E)$ curve and is shown in figure 7.2 panel (b). Note that we use the concept Marginal Cost of Effort, $MC(E)$, in a particular way, namely at the fishery level, describing the addition to total cost of adding one more unit of fishing effort to the fishery. This is somewhat different from the concept of marginal cost at the vessel level, discussed in the preceding chapter. The total cost of effort, $TC(E)$, in figure 7.2 panel (a) is derived from the $MC(E)$ curve. In this case the $TC(E)$ curve is increasing progressively, since the $MC(E)$ curve is upward sloping. The $TR(E)$ curve in Figure 7.2 panel (a) is the sustainable long run total revenue curve, recalled from previous chapters, and the corresponding average revenue, $AR(E)$, and marginal revenue, $MR(E)$, curves are shown in panel (b).

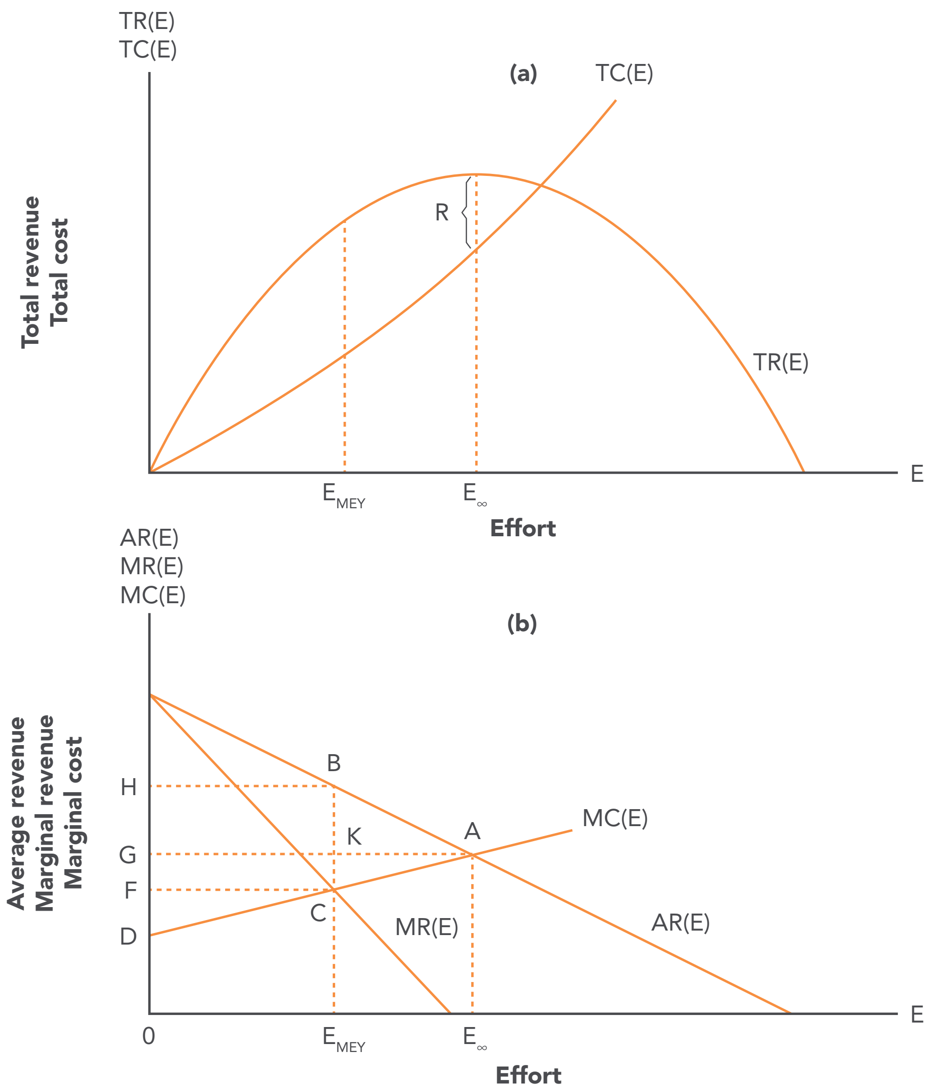


Figure 7.2. Equilibrium fishing effort, resource rent and intra-marginal rent under open-access and under maximum economic yield management in the case of heterogeneous effort.

Open-access equilibrium is found where $MC(E) = AR(E)$, for effort level E_∞. Under open access, vessels will enter the fishery if the average revenue per unit effort is greater than the marginal cost of effort, and exit the fishery if revenue is less than cost. The equilibrium of the open-access fishery is demonstrated in figure 7.2 panel (b). For the effort level E_∞ the total revenue equals the square $AGOE_\infty$ and the total cost equals the area below the $MC(E)$ curve, namely the quadrilateral $ADOE_\infty$. This implies that there is an economic surplus in the fishery, equivalent to the area AGD, since $AGOE_\infty > ADOE_\infty$. This surplus is called intra-marginal rent or producer's surplus.[14] This rent accrues to those vessels that have lower costs than the marginal vessels at E_∞. Note that in figure 7.2 panel (a) the intra-marginal rent is the line segment R. Thus in this case, with a progressively increasing $TC(E)$ curve, the equilibrium point is to the left of the intersection between the $TR(E)$ and the $TC(E)$ curves, the difference between them being the intra-marginal rent.

The total rent of the fishery is defined as

$$\pi(E) = TR(E) - TC(E) \tag{7.1}$$

We discussed at length the maximisation of rent in Chapters 3 and 5, and know that figure 7.2 panel (b) is useful to illustrate the solution. The rent maximising effort level, E_{MEY}, is found where the upward sloping marginal cost of effort curve, $MC(E)$, intersects the downward sloping $MR(E)$ curve. The relationship between revenue, cost and rent is as follows:

Resource rent	$BHFC$
+ Intra-marginal rent	CFD
+ Total cost	$CDOE_{MEY}$
= Total revenue	$BHOE_{MEY}$

The total rent equals the area $BHDC$, in figure 7.2 panel (b), and this is clearly greater than the open-access intra-marginal rent for the open-access fishery, which equals AGD. We notice that even though total rent is greater for the effort level E_{MEY} than for E_∞, the intra-marginal rent is reduced. This may have some implications for management. In case of heterogeneous fishing effort, we have seen that the most cost-efficient vessels do make above-normal profit, called intra-marginal rent. If the fishery manager wants to reduce effort from E_∞ to E_{MEY}, some vessels that have to leave the fishery will lose their part of the intra-marginal rent. This may result in objections to change of management objective. However, as demonstrated above, the total rent is highest for the E_{MEY} effort level, and some of this could be used to compensate those vessels that may be in danger of losing their previous intra-marginal rent. The advice to managers, as a result of this analysis, is to analyse carefully what distributional effects may follow a change in the management system. Otherwise it may be difficult to get the fishermen and the vessels to comply with rules and regulations.

Box 7.1 Economic efficiency of some gill-net fishing vessels in Vietnam

This figure presents an example of heterogeneous cost efficiency of vessels in an offshore fishery in a developing country, where some make a good profit and others a loss. Data for 2008 was collected to study gill-net vessels in Nha Trang, Vietnam, fishing mainly tuna and mackerel in the East Sea (South China Sea). The vessels are about 13–20 m long, have a crew of 8–12 men and an average trip lasts for 16 days. The total cost includes fuel, nets, labour, maintenance, depreciation and interest payment on loans, but excludes calculated interest on the vessel owner's capital. The height of the bars measures the average total cost per unit of standardized effort for each vessel. The unit of effort is put equal to the estimated average effort of the 58 vessels in the sample. The width of a bar indicates the relative effort of each vessel and the vessels are numbered arbitrarily from 1 to 58 (note the difference to the ordering in Figure 7.1). Thus the total effort of all 58 vessels equals 58.0 on the horizontal axis. The horizontal curves $AR_{ws}(E)$ and $AR_{os}(E)$ are the average revenue per unit of standardised effort with and without a lump sum subsidy, respectively, paid by the Government in 2008 only to compensate for the very high fuel costs that year. We see that vessels no.28 and no.49 just break even and that the relative effort of the former is much greater than the latter. On average vessels with the highest effort, which are usually the biggest ones, are also the most cost efficient ones – the bar widths are wider to the left than to the right. However, there are several exceptions, for example vessel no.47 (between no.37 and no.31) to the left and vessel no.13 towards the right. All in all this figure demonstrates what is quite common in the open access fishing industries globally – some vessels and fishermen make good money, others loose.

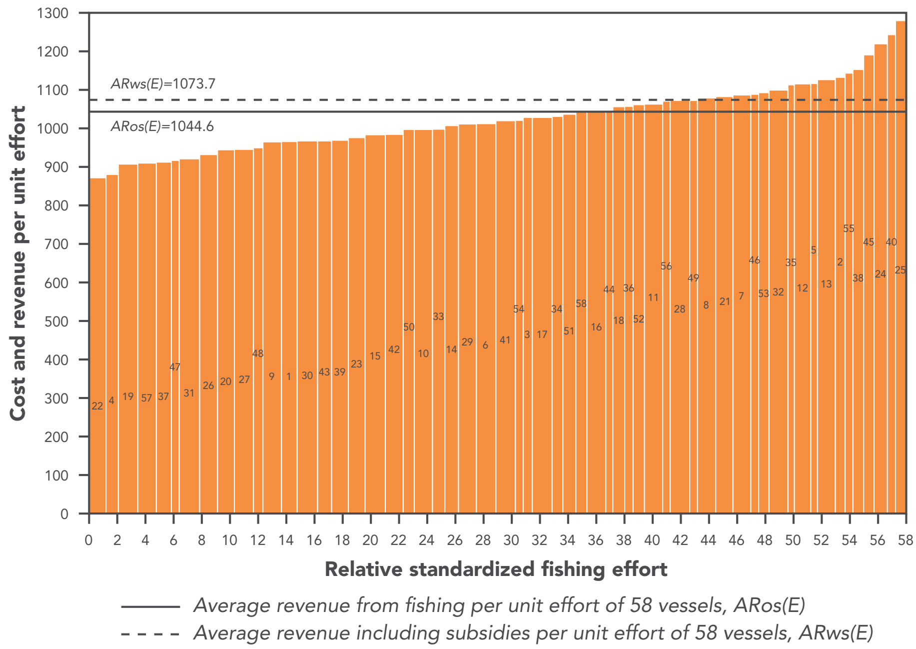


Figure Box 7.1: The cost-efficiency of 58 vessels. In million VND per vessel per year (1 USD=16,950VND).
Source: Duy et al., 2010.

7.2 MARINE RESERVES[15]

Many countries have set aside marine areas for the protection of fish stocks, fauna and flora in the water and on the sea floor, often with the aim of increasing the harvest of fish outside these areas. Such areas are known as marine reserves, nature reserves, marine protected areas, marine managed areas, marine parks, marine sanctuaries, fishery reserves or closed areas, their nomenclature sometimes reflecting local purposes and rules and sometimes arbitrary. Here they are called marine reserves (MRs), indicating that they are protected from human exploitation of fish, either fully or against some types of fishing gear and vessels. Human activities and expansion have contributed to overuse of several terrestrial and marine populations and ecosystems around the world and some populations have even become extinct. Economic and legal instruments to mitigate such problems have been designed and implemented.

In the previous chapters we have mainly focused on resource rent creation as the policy objective and input (licences, effort and capacity) and output (taxes, different types of fish quotas) control as economic policy instruments to achieve the objective. However, in actual policy creation there may be several other objectives, such as preservation of fish stocks and other living organisms in the ecosystem, maximum sustainable yield for food security, consumer and producer surplus, and employment locally or nationally (Box 4.1).

As will be seen below marine reserves (MRs) may contribute to several such objectives, but also may not be particularly suitable for generating resource rent. Also important for the success of the MR are the rules for fishing and other activities outside the reserve. Are there restrictions on the fishermen regarding their choice of vessel, gear and target species? Do they have to pay resource taxes on input or output? Is it an open-access fishery with free entry and exit? To highlight the main features of the MR we will analyse the case of a fully protected fish stock inside the reserve and unrestricted open access outside it with reference to the analyses in chapters 3 and 5.

Marine reserve model

We should expect that the protection of part of a fish stock in one area, the MR, will result in increased biological and economic yields outside the reserve through spillover effects of fish eggs, juveniles and individuals of fishable size. A major question to be answered is how large a part of the total distribution area of the fish stock should be set aside for the MR? Should it be 5, 20 or 40%, for example? The remaining 95, 80 or 60% will be the harvest zone, HZ. The modelling approach is kept simple, so we can investigate analytically to what extent reserve size may be tuned to achieve biological and economic objectives. In the previous analytic chapters fish had no geographical distribution. Now it is distributed across two areas, the MR and the HZ. Even though there may be migration both ways, as indicated by the two uppermost arrows in figure 7.3, the net migration means that fish resources flow from the area with the highest density of fish to a low density area (density is e.g. gram per square metre or ton per square km). Otherwise fish within each area are homogeneously distributed. Without any fishing in the MR the fish density will be highest in this area and fish will spill over to the HZ to allow more resources for the fishing vessels. The analysis is limited to a single stock and questions related to multi-cohort, multi-species, by-catch and ecosystem interactions are not considered for the moment.

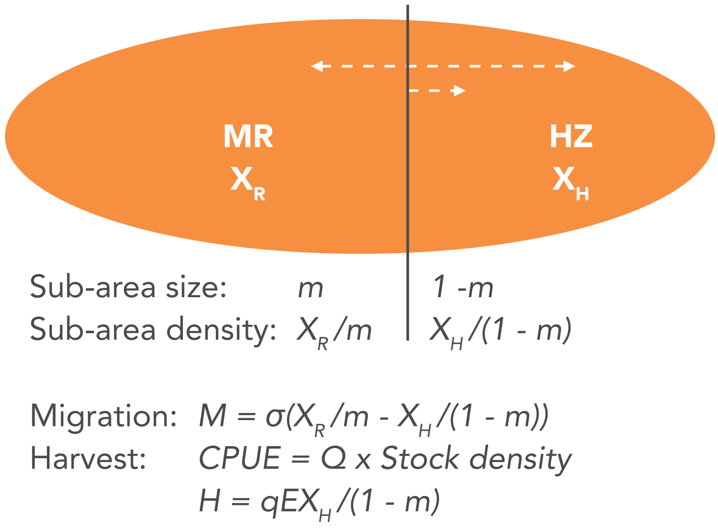


Figure 7.3. The main features of the marine reserve model and analysis. The choice of reserve size *m* is at the forefront of our discussion.

With reference to figure 7.3, before establishing the marine reserve we have a fish stock of size X (measured, for example, in tons) distributed across an area of unit size one (for example, 1.0 km^2). Thus the density of fish is also X (ton per km^2). The growth of this stock follows the logistic growth equation discussed in chapter 5, with natural growth equal to $F(X) = rX(1 - X/K)$, where r is the intrinsic growth rate and K is the carrying capacity. Now the total distribution area of the stock is divided into two parts, as shown in figure 7.3, and the marine reserve is of size m and the harvest area of size $1\text{-}m$. The corresponding sub-stocks are X_R and X_H, respectively, such that $X = X_R + X_H$. The density of fish in each sub-area now depends on both the sub-area size and the size of its sub-stock. Thus the density of fish in the MR and the HZ is X_R/m and $X_H/(1\text{-}m)$, respectively. Recall that in the previous chapters, we did not mention densities of fish, only the stock size, and harvest per unit of effort in the Schaefer harvest function (2.7) is proportional to stock size. As long as the distribution area of the stock stays the same, density will vary proportionally with stock size and implicitly we have taken care of the density of fish. Now, however, it is important to introduce explicitly the density concept since both migration of fish between the two sub-areas and the harvest rate will depend on the densities, and the former on the difference in densities.

Dispersal and migration of fish eggs, juveniles and grown-ups vary with factors such as species, ecosystem, sea current and season, and are the object of research of biologists and other marine scientists. The difference in density between the two sub-areas seems to matter for migration, and we shall assume that the net migration from the MR to the HZ is proportional to the density difference, $M = \sigma[X_R/m - X_H/(1\text{-}m)]$, where σ is the migration coefficient. Thus, if fish is removed from the harvest zone by fishing, the density difference increases and more fish will migrate from the reserve. The bigger σ is the greater is the migration of fish into the harvest zone. In figure 7.3, it is the lower arrow, indicating the net migration *M*, that is of importance in this analysis.

In our analysis, we treat σ as given. Note, however, that the shape of the MR (and the HZ) may affect this migration coefficient in actual cases. If, for example, the population distribution area is a river (like a very narrow rectangle) the migration coefficient is smaller with the two sub-areas downstream and upstream rather than along the left bank and right bank (Flaaten and Mjølhus, 2010).

Open-access harvesting in the HZ

Open-access harvesting takes place in the HZ largely as discussed in chapters 3 and 5. There are, however, a couple of differences. First, for the vessels in the HZ catch per unit of effort is proportional to the density of fish in this sub-area, and according to the Schaefer harvest function harvest now equals $H=qEX_H/(1-m)$ (figure 7.3). Note the difference between this and the harvest function (2.7), which we have used in previous chapters.[16] Second, the quantity and density of fish in the HZ depend on natural growth, as previously, but also on the migration from the MR. With this modelling approach some important management questions may be raised.

Can the marine reserve, combined with open-access harvesting outside, contribute:

- to preservation of fish stocks and other living organisms in the ecosystem,
- to maximum sustainable yield (MSY) for food security,
- to increased employment locally or nationally, and
- to generation of consumer and producer surplus?

Preservation

Stocks threatened by heavy depletion or even extinction by efficient and cheap harvesting, may be increased and preserved by the use of marine reserves. The relative reserve size m needed will vary with harvest efficiency and costs, as well as with the market price of fish. Recall from chapter 5 that the open-access stock level at equilibrium is $X_\infty = \frac{a}{pq}$, where a is the unit cost of effort, p is the price of harvest, and q is the catchability coefficient. Thus X_∞ is positive in the Gordon-Schaefer model with positive effort costs and will not be extinct. However, if costs are low and price and catchability high, the stock may well be heavily depleted. This is particularly so in the case of schooling species (e.g. anchovy, mackerel and herring) in fisheries with purse seine and advanced sonar fish-finding technology. In such fisheries, the threat of stock collapse is much higher than within the Gordon-Schaefer framework where catch per unit effort decreases as stock size is reduced.[17] In our marine reserve model the m needed to keep the equilibrium stock above a specified minimum level increases with p and q and decreases with a. It can also be shown that m has to be bigger the greater the migration rate and the lower the intrinsic growth rate (Flaaten and Mjølhus, 2005). The intuition behind this is as follows. Since the HZ sub-stock is depleted and since migration between the zones depends on relative densities, there will be migration from the nature reserve to the HZ, where the migrating population will then be depleted through harvesting. If the migration rate is greater than the intrinsic growth rate, then the MR sub-population leaves MR faster than reproduction occurs and the population will be heavily reduced, and in extreme case can even become extinct. A sufficiently large reserve will work to protect the overall stock.[18]

Maximum sustainable yield (MSY) for food security

Securing enough protein and food for people nationally may be one of the objectives of fisheries management, though usually not favoured by economists since foodstuff can be efficiently traded internationally. However, let us discuss if marine reserves can contribute to this objective. In chapter 5 the maximum sustainable yield is derived, $MSY=rK/4$, in a single species context, for the Gordon-Schaefer model. Having discussed the ability of an MR to protect the overall stock level, we now ask if this, combined with open-access fishing in the HZ, can realize *MSY*? Is it possible to tune m^* such that effort in the HZ adjusts to what is needed to harvest *MSY*? It will be shown that this is the case but is conditional on economic, biological and technological parameters and also that post-MR growth equals pre-MR growth.[19] A man-made line dividing the habitat of fish into two parts, the MR and HZ (figure 7.3), in itself obviously does not change the growth and behaviour of fish, and this is the approach of this analysis. However, it could be that actually fishing the whole area or just a part of it would make a difference. With harvesting, the latter implies different densities of fish in the two areas with different possibilities for the fish to spawn, find prey and grow (it is left to the reader to investigate the literature for such alternatives; see Flaaten and Mjølhus, 2010 for some references).

For tuning m^* to achieve *MSY* see figure 7.4. Parameter c on the horizontal axis is the pre-reserve equilibrium normalized stock level $c = \frac{a}{pqK}$, varying between zero and one. In low-cost, high-price and technically efficient fisheries the stock will be biologically over-exploited, thus $c<0.50$. In such cases the possibility of tuning m^* to achieve *MSY* is of interest. Figure 7.4 gives, vertically, the m^* needed to realize MSY for different degrees of overfishing pre-reserve. Recall that both pre-reserve and post-reserve there is open-access fishing with equilibrium determined by the parameters. Two biological parameters are of importance for the conclusion, namely the migration coefficient, σ, and the intrinsic growth rate, r. In fact it is merely the ratio between them, $\gamma = \sigma / r$, that is of importance.

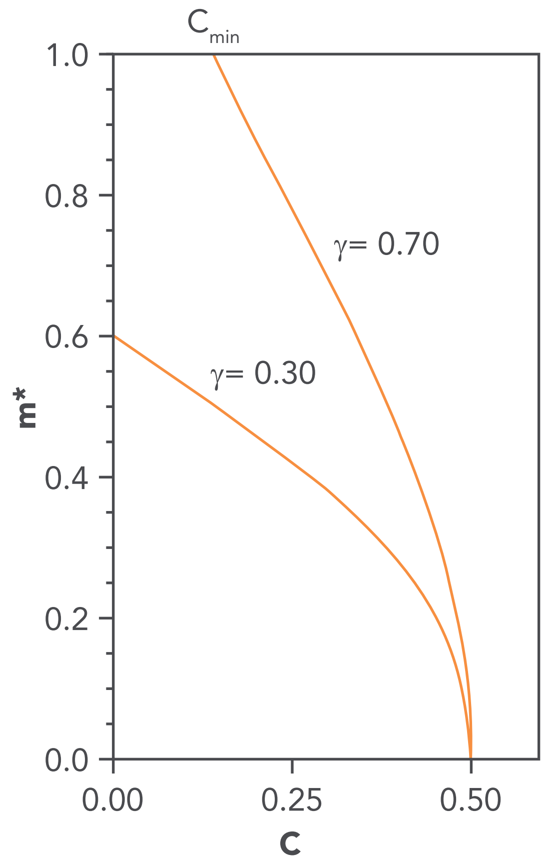


Figure 7.4 Reserve size *m** chosen to realize MSY; downward sloping curves show *m** as a function of the pre-reserve open-access stock level *c*, for two cases, relative migration $\gamma = 0.3 < 1/2$ and $\gamma = 0.7 > 1/2$. Such tuning is not possible when *c* > ½. For the uppermost curve $c_{min} = 1/2 - 1 / 4\gamma = 1/7$ (Flaaten and Mjølhus, 2010).

Note some characteristics of the two curves in figure 7.4. First, only in the case when the resource is biologically overused from open-access harvesting, $c < 0.50$, will the establishment of a permanent MR succeed in realizing *MSY*. Both curves emanate at $c = 0.50$ on the horizontal axis, i.e. at the *MSY* normalized stock level. Second, only the curve for $\gamma = 0.30$ intersects the vertical axis, implying that the MR restricted open-access fishery can realize *MSY* even for very low levels of *c*, provided the MR size is close to 0.60. Third, in the case of a higher γ, $\gamma = 0.70$ in figure 7.4, no MR is large enough to realize *MSY* if *c* is low, $c < c_{min}$. If the stock has been fished down below c_{min}, in figure 7.4 equal to 0.15, a reserve will contribute to increased total stock and to increased harvest, but not enough to realize *MSY*. This is because of the high relative migration rate γ, indicating that the migration of fish from the reserve to the harvest zone is too fast compared with the intrinsic growth needed to build up the stock to the *MSY* level (recall $\gamma = \sigma / r$). In fact, it can be shown that this occurs when $\gamma > 0.50$ since the intersection of the possibility curves with the vertical axis is at $m^* = 2\gamma$ in figure 7.4 (Flaaten and Mjølhus, 2005). Fourth, an MR may help to achieve *MSY* even if γ is higher than 0.50 as long as $c_{min} < c < c_{msy}$, i.e. when on the curve connecting c_{min} at $m^* = 1$ and $c = 0.50$ at $m^* = 0$. To summarize, figure 7.4 demonstrates how MR size must be chosen to realize *MSY* for different combinations of migration, intrinsic growth and pre-reserve stock size – the latter determined by harvest efficiency, price of fish and cost of effort.

As regards nature reserves, monitoring, control and enforcement (MCE) costs may vary with reserve shape, in addition to size. In particular, high population density in a reserve may attract poachers, making reserve geometry of importance. Therefore, reserve design may act as an additional or joint management tool to decide reserve size. For simple geometric forms of the population distribution area the migration coefficient σ may be directly related to reserve size and shape. If, for example, the population distribution area is a river (like a very narrow rectangle) the migration coefficient is smaller with the two sub-areas downstream and upstream rather than along the left bank and right bank. Thus the reserve shape may affect migration between the MR and HZ as well as MCE costs.

Employment

In some countries fisheries are seen as important labour market buffers, particularly in poor countries (Bené et al., 2010), even though we acknowledge the need to restrict effort to create resource rent. Independently of the approach taken, however, it is important to know how effort and catch change when an MR is created. In fisheries, employment is both output-related and input-related; total employment in the sector depends both on effort used in capture and on catch landed for processing, which may be more or less labour-intensive. The possibility of designing an MR to maximize harvest was discussed above, and it is likely that post-harvest employment in processing and distribution of fish increases with harvest. Let us now discuss if effort-related employment at equilibrium changes because of the introduction of an MR. Fishing effort is a composite concept, designed for use in bioeconomic models where it bridges the gap between humans' fishing activities and nature's fish stocks through fishing mortality. In actual fisheries the composition of effort varies, but capital and labour are the core inputs, in addition to other variables such as fuel, gear, bait and ice. Empirical studies have demonstrated that labour increases with effort, proportionally or at a decreasing rate (Squires and Kirkley, 1999; Long et al., 2008).

A reserve is a restriction on the free movement of effort and in general this increases the need for effort in the fishery. This is also the case when *MSY* is achieved with reserve size m^*. Within the modelling approach in this chapter, an MR and open-access harvesting in an HZ may realize *MSY* through increased effort, thus increasing employment in both fish processing and harvesting (for details, see Reithe et al., 2014). For harvest levels other than *MSY* it is necessary to limit the analysis to numerical simulations, and to compare the post-reserve results with the pre-reserve effort and yield for different parameter sets. Higher effort is usually required in the case of an MR than in the pure open-access case. For high levels of effort pre-reserve, resulting in biological overfishing, the protective benefits of the MR ensure a bigger total stock and the migration results in spillover that secures a higher yield. Thus employment with a reserve will be greater than for the overall open-access fishery.

Consumer surplus

For open-access fisheries with constant price of fish and cost of effort, no resource rent, no consumer surplus (CS) and no producer surplus (PS) are generated in the analyses in this and the previous chapters. Then in that case, from an economic perspective, why bother establishing an MR if it does not generate any rent? We have already given some answers to this when discussing stock preservation, sustainable yield and employment. In addition, actual fishing fleets often display heterogeneous vessels and costs – implying PS (intra-marginal rent) in open-access fisheries (see sub-chapter 7.1, including Box 7.1). Also, fish markets often display downward sloping demand and the possibilities of CS, and we will now discuss this. The increased harvest following the creation of an MR, for a biological overfished stock, (see above) combined with a downward sloping demand curve allows for the creation of CS.[20] Now, let us investigate the case of consumer surplus to see how this changes the previous conclusions about zero economic rent. With a downward sloping demand curve for fish, we assume there is a unique stable equilibrium at overall open access. If this is for an overfished stock level, both stock and harvest will be lower the higher the fish price is, all other parameters being constant. This creates a backward-bending supply curve, as opposed to a regular upward-sloping supply curve, known from the theory of production, where quantity increases with price.

Disregarding processing and distribution costs, consumer price equals ex-vessel price and the downward sloping demand implies CS, measured by the area between the demand curve and the equilibrium price. As demonstrated above, tuning reserve size to realize *MSY*, under HZ open access, may or may not be possible, depending on biological and economic parameters. The case of biological over-exploitation pre-MR and open-access harvesting in the HZ post-MR implies increased harvest as well as increased consumer surplus when demand is downward-sloping. This is clearly an economic benefit of MR creation for over-exploited resources. Consumer surplus may be of great importance for some resources, such as those harvested and used for easily perishable food at local or national markets limited in size.

Producer surplus

We discussed heterogeneous vessels in sub-chapter 7.1. With such a fishing fleet, usually thought to be a more realistic assumption for modelling, total cost of fishing will be non-linear. The most efficient vessels will earn a super-normal profit in spite of open access. This rent, the intra-marginal rent or producer surplus (PS), is discussed in figure 7.2 and may be estimated from cost and earnings data (for an example of cost data see Box 7.1). Now the question is whether an MR as the only policy instrument can potentially increase PS. In the light of the analysis in Reithe et al. (2014) the answer is mainly affirmative.

Open-access equilibrium effort is found where average revenue *AR(E)* is equal to marginal cost *MC(E)* (chapter 3). With no MR and total costs now assumed to be quadratic in effort, $C = \alpha E^2$, equilibrium open-access effort and stock will be given by $E^\infty = pr/(pr+2\alpha)$ and $S^\infty = 2\alpha/(pr+2\alpha)$, respectively. Thus, E^∞ decreases and S^∞ increases with the cost parameter α. In other words, this qualitative result is similar to that of the Gordon-Schaefer model with a linear total cost function; open-access equilibrium effort decreases and stock increases with the unit cost of effort, and PS decreases. The parameter α determines the open-access equilibrium both pre-reserve and post-reserve and PS will be greater the smaller α is. For a biological over-exploited stock pre-reserve an MR will increase PS when there is HZ fishing, for parameters discussed in figure 7.4; that is for an over-exploited stock and relative migration, α, between 0.3 and 0.7 (Reithe et al., 2014). An MR of any moderate size will cause equilibrium effort, and hence also PS, to increase. However, if the reserve is made "too large" effort and PS may decrease compared with the pure open-access case.

Concluding remarks on marine reserves

It is well known (see chapters 3 and 5) that no rent is generated under open access within the Gordon-Schaefer model with constant price of fish and homogeneous effort. However, we also know that small changes in the underlying assumptions may allow for rent generation, in particular consumer and producer surplus, as demonstrated in this chapter. (See Box 7.1 for a related empirical study.) We have discussed the possibility of such rent generation by use of a marine reserve with open-access fishing outside. However, maximizing total economic rent may of course not be the only objective of fisheries management. Therefore, this MR approach also considers what is usually classified as ecological objectives, namely resource conservation and restoration and maximum sustainable yield, as well as social objectives, such as employment and food security.

For developing countries, which typically have fisheries in tropical ecosystems characterized by a high number of species and mixed fisheries, limited resources available for fisheries management and a high degree of subsistence and small-scale fisheries, the management tools often used by industrialized countries are not suitable. Taxing or controlling the harvest of thousands of vessels, each catching a small amount which is sold on local markets, would be very demanding. Fisheries management does not come for free and monitoring, control and enforcement are not perfect, usually resulting in some IUU fishing (Schrank et al., 2003). As regards actual management the efficiency and costs of different instruments should be an integral part of the policy discussion. OECD fishing countries from 1987 to 2007 saw a decline in fish catches of about 2% per year on average, whereas the other fishing nations worldwide had an annual increase of about 2%, despite the more advanced instruments of the former (Flaaten, 2013). Because of overfishing and decline in catches in several member countries the OECD has instigated discussions and analyses to mitigate such problems (OECD, 2012 and 2013). Controlling fish in a particular area (MR) is easier and cheaper than conventional input and output control, but it is essential to know how closing an area will affect stocks, harvest, vessels and labour, and if any economic and social benefits could be generated by doing so (Reithe et al., 2014 p. 35).

In the fisheries management literature other factors, such as enhancing food security and food safety, inter-generational equity, reducing vulnerability to external shocks from foreign exchange fluctuations and extreme climatic events, have been suggested to play a role in the establishment and maintenance of marine reserves. Some may be included in a bioeconomic analysis of marine reserves, whereas others are beyond the scope of what economists can do; they are beyond the scope of this study and require environmental, social and political tools of analysis. From an economic perspective the long-term cost-effectiveness of marine reserves compared with other management tools should be at the forefront of analysis.

8 GROWTH AND YIELD OF YEAR CLASSES

In this chapter we analyse the effects on yield and economic rent of changes in technical fisheries regulations by use of a year class model. It is shown that technical regulations such as minimum mesh size can realise greater long-term yield and economic rent if fishing mortality is controlled simultaneously. Fisheries biologists usually use year class models in their stock assessment and advisory work.

8.1 GROWTH AND AGEING

In Chapter 2 it was noted that the biological processes that generate bell-formed growth curves include individual growth, recruitment and natural mortality. Even though a fish stock may consist of several year classes, of which just the older ones spawn and ensure recruitment to the stock, and young fish may have a higher growth rate than the older ones, bell-shaped growth curves incorporate all such processes. In addition, as have been shown in the previous chapters, the growth curves form a good foundation for economic analysis of fishing. However, there are at least two reasons for also studying fisheries adaptation and management within a year class framework. First, a year class model may increase our understanding of the biological and economic effects of technical regulations. Second, fishery scientists in actual assessment and advisory work extensively use year class models. When working with detailed and complex year class models we must be aware that even in such models we can find the maximum sustainable yield (MSY) and the corresponding stock size, though these characteristics are not as apparent as in the aggregated biomass models. Fisheries management in many parts of the world is dominated by analysis and management advice from biologists and other natural science researchers, who base their work mainly on disaggregated models. Such models specify in more or less detail the three biological processes – recruitment, growth and mortality – of the year classes of the stock. Therefore, let us have a closer look at such population models and how they may be used for economic analysis.

A cohort is a group of fish of the same age belonging to the same stock. That is why year class models are often called cohort models. In the temperate zones of the world fish stocks usually have only one spawning season per year, thus producing one cohort per year. However, fish stocks in tropical areas, where spawning can take place throughout the year, may produce two or more cohorts annually.

Fish usually grow throughout their lives, but at a decreasing relative rate both with respect to length and weight. This contrasts with humans and many other animals whose growth ceases some time after adolescence. The growth of a single fish may depend on the available food, water temperature and other biotic and abiotic factors, in addition to its basic physiological characteristics. Even though there may be a great variation of growth within a cohort, it is useful to describe the average growth of fish by use of a graph or an equation. Figure 8.1 shows the estimated age-specific length and weight of Northeast Arctic cod, and figure 8.2 shows the estimated age-specific length and weight of Pacific mackerel. Note that length increases at a decreasing rate for both species throughout the life of the fish, whereas weight increases at an increasing rate until the age of around eight years for cod and five years for mackerel. Actual data will typically be dotted above and below the growth curve, with the curve depicting the average value at each age. That is why fish actually can be longer and heavier than the asymptotic values shown in these figures.

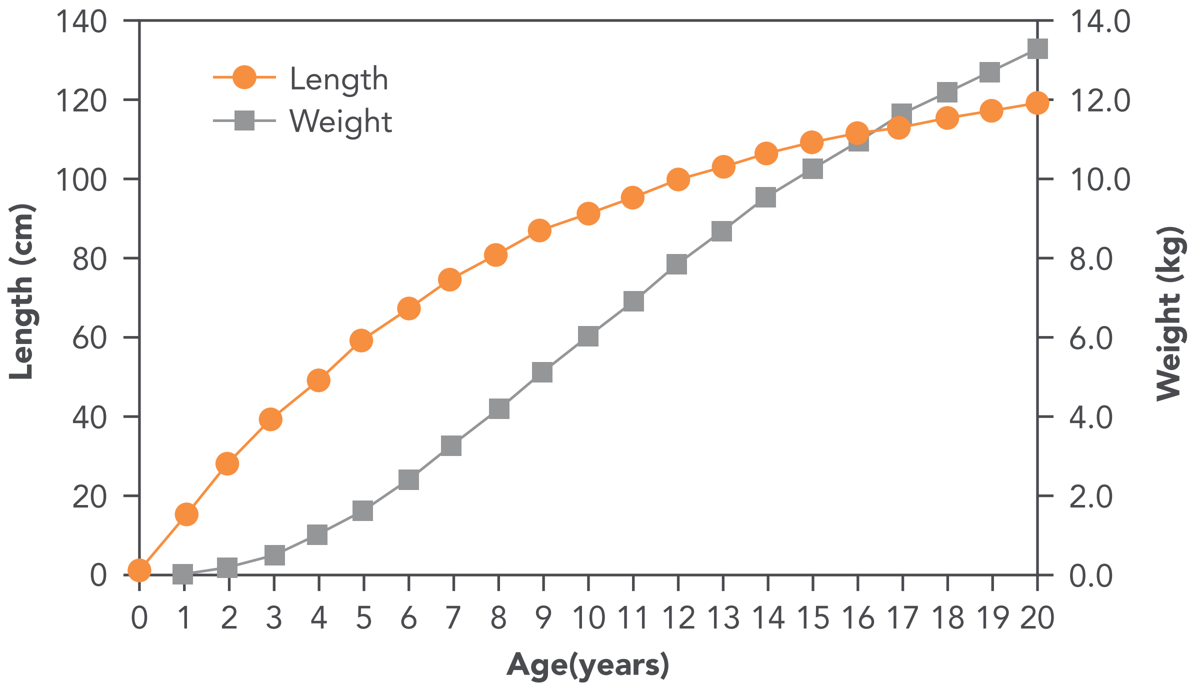


Figure 8.1 Average length and weight at age of Northeast Arctic cod portrayed by use of the von Bertanlanffy growth equation. Parameter values are: k = 0.12, l_∞ = 130 cm, w_∞ = 17.00 kg, t_0 = 0.
Source: Parameter values from Sullivan (1991).

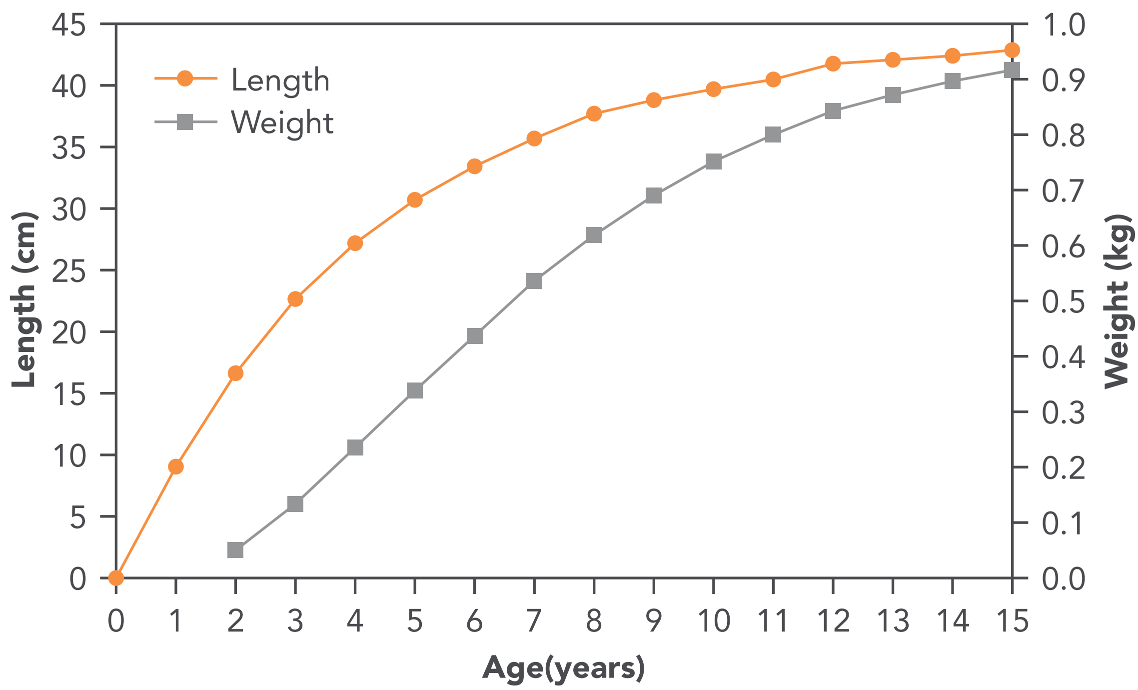


Figure 8.2. Average length and weight of Pacific mackerel depicted by use of the von Bertanlanffy growth equation. Parameter values are: k = 0.24, l_∞ = 44 cm, w_∞ = 1.00 kg, t_0 = 0.
Source: Parameter values from Sullivan (1991).

There are more than one species of both cod and mackerel, and several stocks, in both the Atlantic and the Pacific. Growth rates vary between areas due to differences in sea temperature, food availability, and other factors. Mackerel is a pelagic species that grows relatively fast at a young age and reaches maturity already after two to four years. Cod is a relatively slow growing but long-lived species that can reach the age of 20 or 30 years, and it reaches a significant length and weight.

The length at age curves in figures 8.1 and 8.2 are calculated on the basis of the von Bertalanffy (1938) length growth equation

$$l(t) = l_\infty(1 - e^{-k(t-t_0)}) . \tag{8.1}$$

The weight at age curves in figures 8.1 and 8.2 are calculated on the basis of the von Bertalanffy weight growth equation

$$w(t) = w_\infty(1 - e^{-k(t-t_0)})^3 . \tag{8.2}$$

Each of equations (8.1) and (8.2) describes the growth of individuals by use of three parameters. Other functional forms have also been used for curve fitting of fish growth, but the von Bertanlanffy equations are the most common (see, for example, the FishBase web page). Parameter l_∞ is the maximum length of the fish, to be reached only at a very advanced age – really at an infinitely high age, mathematically speaking. Parameter k, together with l_∞, contributes to the relative growth of fish. Note that even though k usually is called the growth parameter, length growth is really a function of both k and l_∞. The parameter k is usually smaller for big fish, such as cod and halibut, than for small fish, such as pilchard and sprat (for lots of examples see FishBase at http://www.fishbase.org/search.php). At a very young age, as larvae or juvenile, fish may have another growth pattern from that during the later stages of life. Parameter t_0 tells the hypothetical age at which the fish would have had length zero if growth followed the normal pattern throughout life. (To see that $l(t_0) = 0$, substitute t_0 for t in equation (8.1).) Technically, t_0 may be positive, negative or zero. However, for the growth curves shown in figures 8.1 and 8.2 t_0 has been fixed to zero, to simplify the estimation process, figures and comparison between species. (For a thorough review of estimation methods for parameters in growth functions, and in other fisheries equations and models, see Haddon (2001).)

If we follow a cohort of fish throughout time there will typically be a gradual reduction in the number of individuals from the birth of the cohort to the point in time when the last individual dies. There are great variations between stocks in how fast a cohort is reduced in size. Some marine species, for example, seals, have a few offspring with a low natural mortality, whereas others, for example, mackerel, have a huge number of offspring, with a high natural mortality. The most common cause of natural mortality of fish is predation from other fish, sea birds and sea mammals. The smaller a fish is the more individuals in the sea are able to eat it, thus implying a high rate of mortality from predation. It is not uncommon that mortality due to predation on fish eggs and fries exceeds 10–20 per cent per day. For adult fish, however, daily rates of mortality may be down to a fraction of one per cent. In addition to predation, other natural causes of death of fish include illness, starvation, parasites and poisoning. Such causes often weaken the fish to make it more vulnerable to predation – thus fulfilling the saying: one man's death is the other's life.

For management purposes it is important to distinguish between natural mortality on the one hand and fishing mortality on the other. Fishing means removal of fish from the sea, thus adding to the total mortality of the cohort. For managers, an important question is how many fish should be removed from the cohort and how many should be left in the sea. (We shall come back to this at a later stage). Total mortality, denoted Z, consists of the sum of natural mortality, denoted M, and fishing mortality, denoted F. First, let us have a closer look at the effects of natural mortality on the surviving number of fish. Disregarding the very early stages of the life of a fish, natural mortality seems to be a relative constant fraction of the number of fish. This means that, disregarding fishing, for example, 20 per cent of the cohort will die from natural causes from one year to the next. However, fish typically die every day and minute throughout the year, and for this reason it has proved practical to count mortality on an instantaneous basis. Recalling Chapter 4 we have seen that, regarding discounting, it is rather a question of convenience whether we should use discrete or continuous time for the calculation of present value and compound[21] interest. The same applies to the development of a cohort over time. Fisheries biologists tend to use continuous time when calculating natural and fishing mortality in a management context. Therefore, we shall use the same approach.

Starting with N_0 fish, the number of fish will have decreased to

$$N(t) = N_0 \, e^{-Zt} \qquad (8.3)$$

at time t if the total instantaneous mortality rate, $Z = M + F$, is constant.

For some species, such as salmon, most fish die after spawning, implying that M is extremely high during the post-spawning period. However, for most fish species of commercial value, natural mortality, M, is in the range of between 0.1 and 0.8.

Box 8.1 Fishing mortality in a fish farm

Farming of salmon, and other big fish, is an extreme example of single cohort fishing. For each new round of production, farmers usually put some thousands of juveniles of the same cohort into the cage. After having fed and tended the fish for a couple of years, the stock may be harvested during a very short period of time. Let us have a closer look at a numerical example to see how great the fishing mortality F can be in the case of fish farming. A cage contains 60 000 salmon at time t, that is N(t) = 60 000. The harvest takes place during five days, which implies that dN = 60 000 and dt = 5 / 365 = 0.0137 when time is measured in years. Neglecting natural mortality this implies

$$dN / dt = -F \, N(t) \,. \qquad (1)$$

Based on equation (1) and the data given above we derive F = 73.0. This is an extremely high fishing mortality compared with the harvesting of wild fish. However, F > 1 is not unknown in commercial fisheries, in particular in the case of fast growing short-lived species. Note that F =1 does not imply that the whole cohort is fished in one year (see exercise 8.1).

Small fish, such as sprat and pilchard, usually have higher M than bigger fish, such as cod and halibut.

Multiplying the number of fish in equation (8.3) with the individual weight in equation (8.2) gives the biomass at age t

$$B(t) = w(t) N(t) \,. \qquad (8.4)$$

Figure 8.3 shows the development of a mackerel cohort in numbers and total weight, or biomass. In this case with a natural mortality M = 0.4 and no fishing (F = 0) the number of fish decreases from one billion recruits at time zero to approximately 200 million at the age of four and 135 million at the age of five. Thus after four years there will be only one in five fishes left in the cohort. The natural mortality used in this example fits the Pacific mackerel, but the number of recruits is arbitrarily chosen (low).

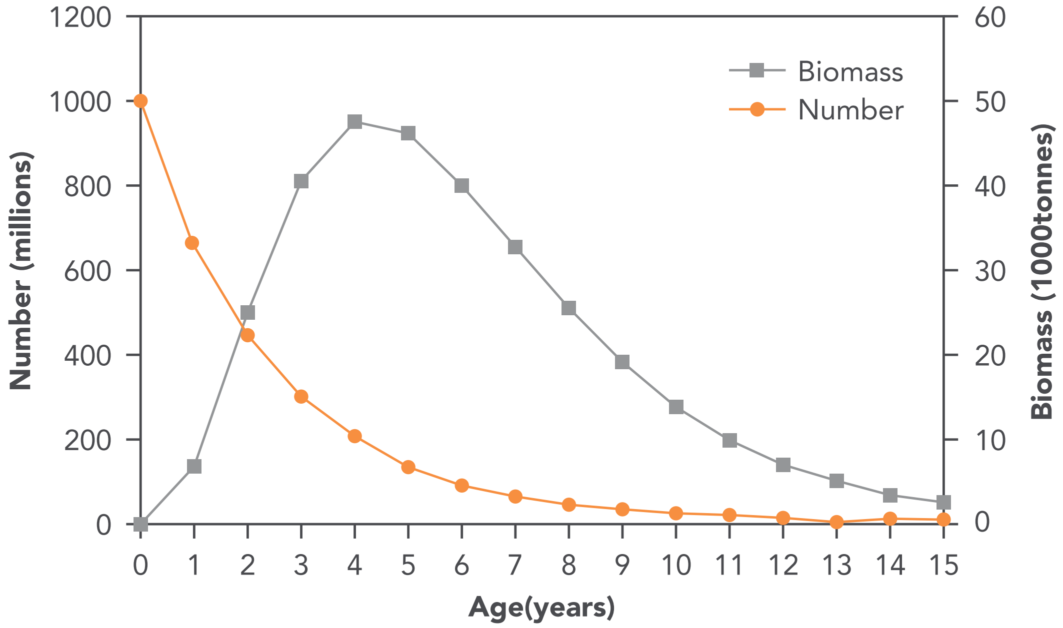


Figure 8.3. The decline in number of fishes and the rise and decline of biomass in a given cohort of mackerel, without fishing. Parameters used are $N(0)$ = 1 billion, M = 0.4 and growth parameters as in figure 8.2.

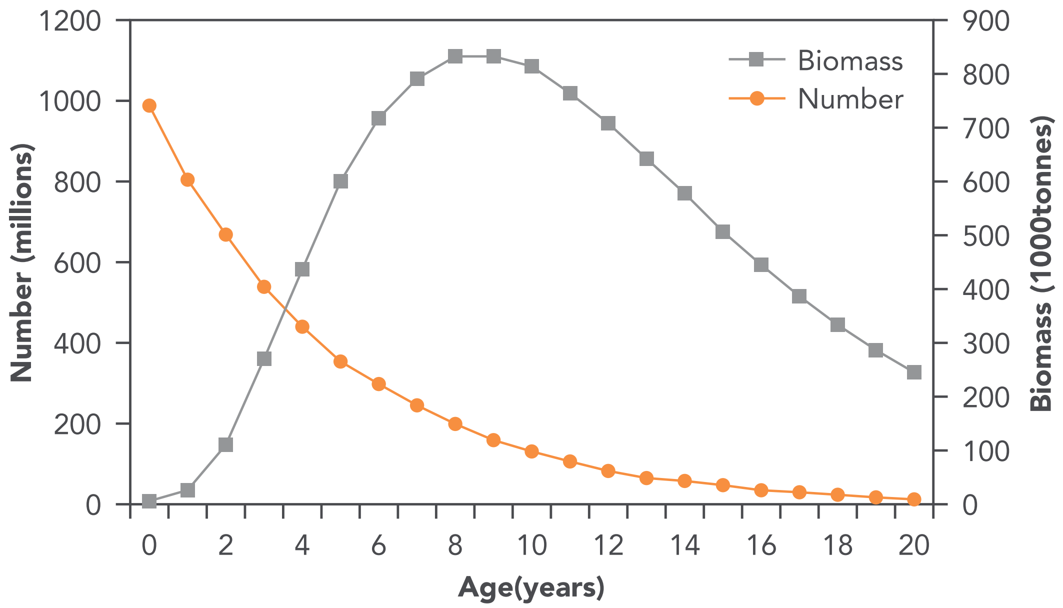


Figure 8.4. The decline in number of fishes and the rise and decline of biomass of a cod cohort, without fishing. Parameters used are $N(0)$ = 1 billion, M = 0.2 and growth parameters as in figure 8.1.

Figure 8.4 shows the development of a cohort of cod in number and total weight, or biomass. In this case with a natural mortality $M = 0.2$ and no fishing ($F = 0$) the number of fish decreases from one billion recruits at time zero to approximately 420 million at the age of four and 200 million at the age of eight. Thus after four years there will be just above four in ten fishes left in the cohort and at the age of eight there will be two in ten fishes left. The natural mortality used in this example fits the Northeast Arctic cod. The number of recruits in figure 8.4 is arbitrarily chosen, but is within observed limits for this cod stock.

Multiplying number of fish by the individual weight gives the age-specific biomass curve shown in figures 8.3 and 8.4. Thus the total weight, the biomass of a cohort, depends on the weight of single fish and the number of fish. Biomass typically increases progressively (convex) during the early stage of life, then continues to grow but slower and slower (concave) until it reaches its maximum. From this maximum the biomass decreases gradually towards zero at the maximum age of the fish. This maximum age is usually much higher than the average age of harvested fish. The maximum age is the age a fish of a given stock could reach if it were left un-harvested by man and predators. The particular biomass curve shown in figures 8.3 and 8.4 are based on the weight curves of Pacific mackerel and Northeast Arctic cod, respectively. In the case of mackerel the cohort reaches its maximum biomass at the age of four years, whereas in the case of cod the cohort reaches its maximum biomass at the age of nine, in both cases with the assumption of no fishing. The age that gives biomass maximum of a cohort depends on the biological characteristics of the fish stock. Higher natural mortality M, ceteris paribus, means a lower age at biomass maximum.

As noted above the age-specific biomass curves shown in figures 8.3 and 8.4 are based on the absence of fishing. If and when fishing takes place, the biomass growth will be slower and the decline will be faster than shown. In actual fisheries the gear type in use often determines what sizes of fish are caught and what sizes escape. For example, a fisher's choice of gill-net mesh size usually depends on his targeted fish species and size. Small fish have a greater probability than big fish of avoiding being entangled in the net. This probability increases the smaller the fish is, since the little ones pass through the meshes more easily without being trapped. However, a big fish also has a positive probability of escaping the gill net, because it is not entangled or it has the power to free itself from the net. Thus a gill net typically catches most medium-sized fish, and this "medium size" depends on the mesh size. On the other hand, trawl has the property of keeping few of the small fish, most medium-sized fish and all the big ones that encounter the gear. For very small fish, trawl takes none at all. For example, bottom trawl used for cod-like fish does not catch shrimp, even if such a species is present on the fishing ground.

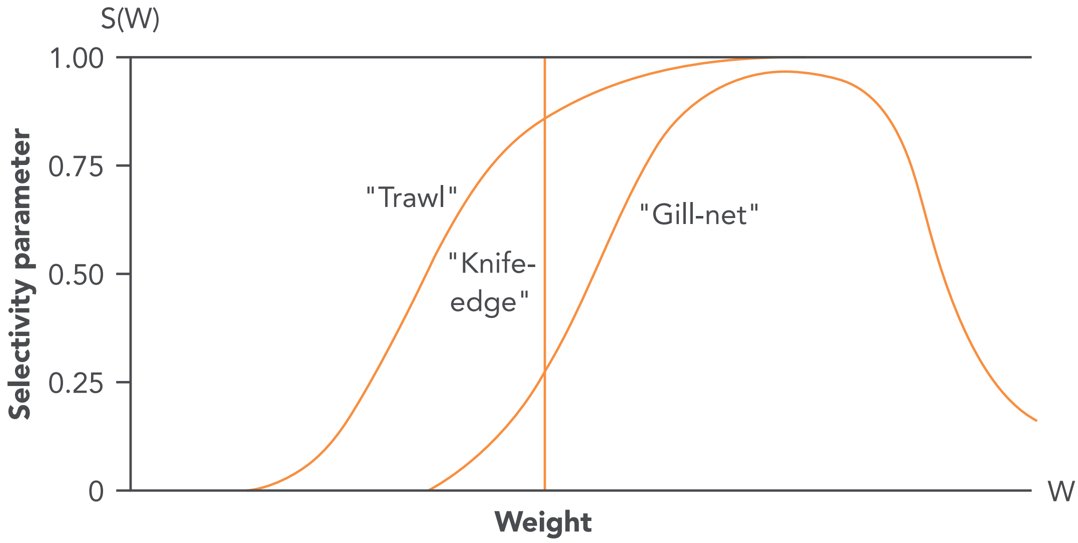


Figure 8.5. Selectivity curves for three types of fishing gear.

The selectivity pattern varies across gear type and this pattern may be described by use of selectivity curves. Figure 8.5 shows three examples of selectivity curves, namely size dependent selectivity for gill-net and trawl as well as knife-edge selectivity. For analytical purposes it is often convenient to assume knife-edge selectivity to focus on the harvest potential of a fish stock. Even though knife-edge selectivity is hard to achieve in actual fisheries, bottom trawl with steel or alloy grids that substitute parts of the net may come close to this. The grid will stay open with a fixed distance between the bars, allowing all or most fish below a certain thickness to escape the gear independent of how many fish are in the cod-end of the trawl. Most gear has a somewhat more complicated selectivity pattern than knife-edge selectivity, for example, like bell-shaped or s-shaped curves. In conventional trawl, the net is gradually stretched and the real mesh size reduces as more and more fish accumulate in the trawl, thus effectively decreasing the selectivity properties of the gear. In general, the selectivity curve of gill-net is bell-shaped and that of conventional trawl is s-shaped. The values of the selectivity parameter vary between zero and one, telling the probability of a fish encountered by the gear being trapped as a function of the size of the fish. Knife-edge selectivity exists when the selectivity parameter is zero for small fish up to a given size and one for all sizes equal to or bigger than this minimum catchable size. Most gear types do not catch the very smallest fish. What "smallest" means varies across type of gear and mesh size.

With a direct relationship between fish size and age, as we see in figures 8.1 and 8.2, the first-age-of-capture, t_c, is the age that corresponds to the minimum catchable size. In the case of knife-edge selectivity the definition of t_c is clear, namely the age at which fish reaches its minimum catchable size. However, for practical purposes in the case of size variable selectivity of trawl t_c must be related to the age that gives, for example, $s(w) = 0.25$ and for gill-net t_c may be defined as the lower age for which, for example, $s(w) = 0.25$. Note that in the bell-shaped selectivity curve for gill-net there are two weight (age) classes of fish that give for example $s(w) = 0.25$, whereas for trawl there is only one.

8.2 SUSTAINABLE YIELD AND ECONOMIC SURPLUS

With knife-edge selectivity and constant fishing mortality throughout each cohort's life the yield from this cohort depends on the mesh size and the fishing mortality.

Figure 8.6 shows the yield curves for cod for three different age-of-first-capture, t_c. In this case we have drawn the picture of total yield (the eumetric yield is explained below). A quite similar picture would appear if we divide total yield by the number of recruits at t_0 and depict yield per recruit. In fact, in the biological literature yield per recruit is more common than total yield in this connection.[22] Note that the curves for zero and three years of first capture have a distinct maximum whereas the curve for nine years does not have such a maximum. This is because the biomass maximum of the cohort is reached at the age just below nine, at 8.6, as shown in figure 8.4. Any yield curve with t_c equal to or greater than the age of natural biomass maximum (without fishing) will be without a distinct maximum point. The fishing mortality that gives the maximum yield, for a given first age of capture, t_c, is called F_{max}. This is a biological reference point that tells what the fishing mortality should be for the fishery to produce maximum yield, given knife-edge selectivity and a specific age of first capture. In figure 8.6 we have two values of F_{max}, one for age 0 and one for age 3. Fisheries biologists use F_{max} and several other biological reference points in their assessment and advisory work (for a review, see, Caddy and Mahon, 1995).

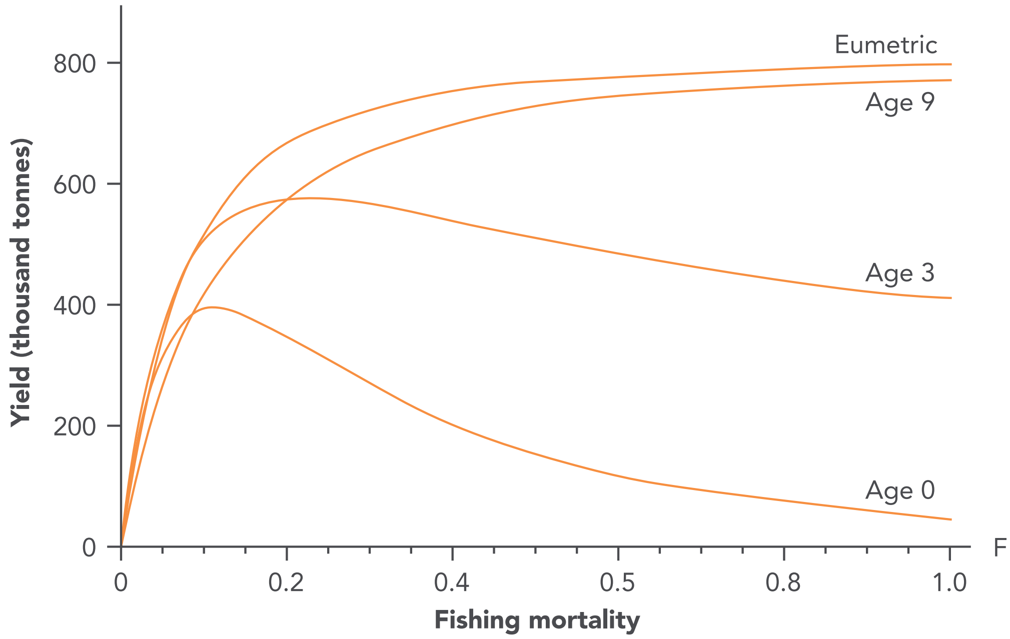


Figure 8.6. Yield curves of cod for three different age-of-first-capture, namely 0, 3and 9 year as well as eumetric yield, based on knife-edge gear selectivity. Parameter values of growth are as in figure 8.1, $N(0)$ = 1 billion and M = 0.2.

Note that the catch will consist of fish at or above the age of first capture t_c, as long as the fishing mortality is within reasonable limits and the stock consists of several year classes. Some fish will survive fishing and reach an age well above t_c. A fish stock will typically consist of a higher proportion of old fish the lower the fishing pressure has been throughout some period of time.

Figure 8.6 clearly demonstrates that it is the combination of mesh size and fishing mortality that determines the possible yield of a cohort. If, for example, fishers use an extremely small mesh size, with the age of first capture close to zero, and a high fishing mortality, the yield from this cohort will usually be low. However, if the fishing mortality is kept low, even with such a small mesh size the yield may be significant. Figure 8.6 shows that the combination of age of first capture equal to zero and fishing mortality equal to 0.1 would yield almost 400 000 tonnes, which is about half of the maximum yield. However, to obtain the maximum yield it is necessary to have a high first-age-of-capture, almost nine years, and a high fishing mortality, about 1.0 or higher. Thus this cohort analysis demonstrates the need for simultaneous mesh size and fishing mortality control. So what combination should the manager aim at? To answer this question we shall have to include economic issues in the analysis of cohort fishing.

For the mackerel cohort shown in figure 8.3 the maximum biomass occurs at the age of four and for cod shown in figure 8.4 the maximum occurs at the age of almost nine. However, such a maximum can be harvested only by use of an infinitely high fishing mortality exactly when the biomass reaches its maximum. Theoretically, at this point in time the total cohort is harvested by unlimited use of the knife-edge selective gear. However, from an economic point of view it is easy to understand that this is not a very useful concept of optimal fishing. Infinitely high fishing mortality and effort would imply infinitely high costs. Therefore, for an economic approach to cohort fishing we introduce the concept of eumetric yield curve.[23] For each value of F in figure 8.6 there exists some mesh size that gives the maximum sustained yield. The resulting curve through these maxima is the tangent to each of the size selective yield curves. We could also say that the eumetric yield curve is the envelopment of the individual mesh size conditional curves, as show in figure 8.6.

We discussed in chapter 2 how harvest may depend on stock size. One of the simplest relationships between stock size and harvest is the case of proportionality. For a cohort fishery this means that harvest is proportional also to the number of fish

$$Y = FN, \tag{8.5}$$

where Y = catch in number of fish. If fishing mortality is proportional to fishing effort, E, we have

$$F = qE\,, \tag{8.6}$$

where q is the catchability coefficient. Combining (8.5) and (8.6) gives the Schaefer harvest function in number of fish:

$$Y = qEN\,, \tag{8.7}$$

in the case of cohort fishing. Since the eumetric yield is the greatest possible yield that can be obtained for each level of fishing mortality, F, this holds also for each level of fishing effort E = F devided by q.

Let us use these catch equations for an economic analysis of the cohort fishery, recalling that eumetric yield means that both fishing effort and mesh size are optimally adapted. If the fishing industry is a small part of the national economy it is reasonable to assume that effort can be expanded at a constant cost per unit and that fish may be sold at a constant price per unit harvest. Total cost is

$$TC = aE, \tag{8.8}$$

where a = cost per unit effort. By combining equations (8.6) and (8.8) it follows easily that cost per unit fishing mortality is $a_F = a/q$. The actual value of a_F tends to be a large number since F is a small number, whereas the value of a depends on the choice of unit for measuring fishing effort. Whether effort is measured in, for example, trawler year or trawl hour makes a great difference to the value of a.

Figure 8.7 shows how revenue and costs may increase with fishing effort. In this case there are four revenue curves, corresponding to the three age-of-first-capture specific and the eumetric yield curves in figure 8.6. With a constant price, p, per unit harvest independent of fish size, the revenue curves in figure 8.7 is just a rescaling of the yield curves in the figure 8.6. For most types of gear the cost per unit effort varies very little with mesh size and selectivity pattern of the gear. This is why there is only one total cost curve in figure 8.7. In this case we assume that cost per unit effort and total cost are independent of mesh size and age-of-first-capture. Note that the main difference between figures 8.7 and 3.1 is that the former displays four possible revenue curves whereas the latter has only one. Even though biomass models are often used for analysis of multi-cohort fisheries, they do not explicitly consider selectivity effects.

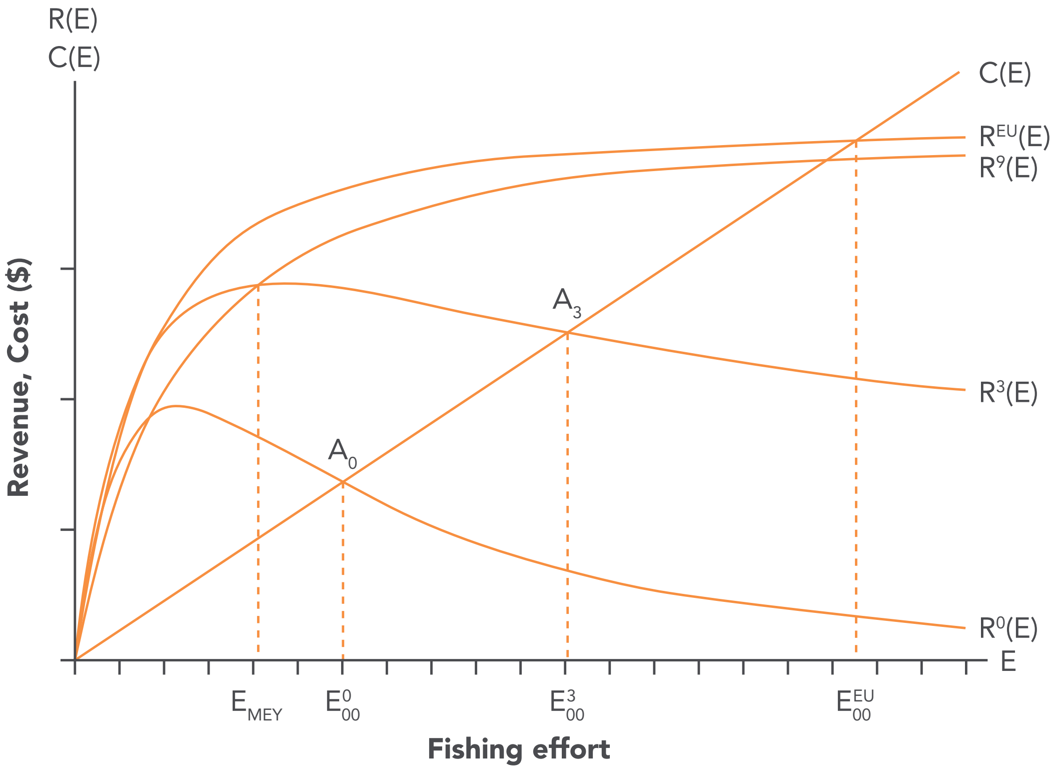


Figure 8.7 Revenue and cost curves for cohort fisheries, with revenue depending proportionally on and cost independent of the type of yield curve.

Let us now use figure 8.7 to analyse and compare the open access (OA) and the maximum economic rent (MEY, where Y denotes yield) fishing regimes. For an OA fishery **with no technical regulations** we would expect fishers to catch any fish of commercial value. If even the smallest fish attracts the price p, fishers would choose the smallest mesh size available and keep for sale any fish they catch. In figure 8.7 this means that the OA equilibrium will be at A_0 for the rent dissipating effort level E^0_{00}. However, assume the fisheries manager introduces a technical regulation demanding all fishers use a mesh size that effectively increases the age of first capture to three years. This means that the R_3 curve in figure 8.7 will be the actual revenue curve for the fishery. OA fishing implies that the equilibrium changes from A_0 to A_3 with higher revenue, cost and effort compared to the OA fishery with no technical regulation. Technical regulations may contribute to the overall size of the fishery, but as the only management tool, no rent will be generated.[24] The resource rent is maximised for the effort level E_{MEY}, where we find the greatest distance between the R and C curves. To realise this optimum the management authority has to limit, directly or indirectly, the amount of effort in the fishery, and simultaneously limit the mesh size to achieve the eumetric yield. Compared with the economic analysis of the biomass fishery in the previous chapters, we now see the need for at least two management tools: firstly, a technical regulation to avoid harvest of small fish, and secondly, some control to avoid excessive fishing mortality. The latter may be achieved by input control or output control, as discussed in Chapter 3.

The simplicity of figure 8.7 should not lead us to the conclusion that the only difference between a cohort model and a biomass model is the introduction of a first age of capture or a mesh-size parameter in the former. In fact, a cohort model with several year classes and a stock-recruitment relationship may be incredibly complex from a dynamic point of view (see Clark, 1990, ch. 9). The above analysis of a cohort fishery is based on the assumption of constant recruitment and fixed age-dependent individual growth. In other words there are no density-dependent processes that reduce recruitment at low stock levels or reduce individual growth at high stock levels. For actual fish stocks, recruitment usually depends on both spawning stock size and environmental conditions, and growth of individual fish may slow down at high stock levels due to competition for food. Fish has to grow for some years to mature and reproduce, therefore the number of recruits to the fishable stock depends on the spawning stock size one or more years before. The length of this time lag between spawning and recruitment varies across species and stocks. Adding multi-cohort, stock recruitment and time lag to the cohort analysis above could make the analysis too complex for analytical solutions to be found. A common solution to such problems is to use numerical model simulations. The need for technical regulations of a fishery is likely to become even more prevalent within such a framework.

Groups of year classes of a given fish stock may have different migration patterns due to different needs. The spawning cohorts, for example, need suitable spawning grounds at a time of the year when the chances of offspring survival is good. Juvenile cohorts grow relatively fast (as seen in figures 8.1 and 8.2) and they need a large amount of food. Therefore, younger generations of fish tend to migrate across season and area to find suitable and plentiful food. Migration of fish for spawning, feeding or other biological reasons may imply a need for additional management tools, such as area and seasonal restrictions on fishing. However, from an economic point of view, it is important to distinguish between management tools that increase the net revenue (resource rent) of a fishery and tools that mainly increase harvest costs. An example of the latter is when fishers are restricted from harvesting where and when the fish is easiest and least costly to catch. However, restricting access to harvesting the spawning stock through area and seasonal closure may be economically sound if this protects spawners and increases future recruitment. The stock-recruitment relationship is important for the long-term yield and the economic performance of the fisheries. It is important to stress that technical regulation of, for example, gear selectivity, area and seasonal closure, should be designed to increase the long-term profitability of the fishery. Unfortunately, in fisheries around the world there are several examples of actual regulations that inflict costs on the industry without increasing yield and revenues (see, for example, Shrank et al., 2003).

Exercise 8.1.

In a cod fishery fishing mortality is proportional to fishing effort ($F = qE$) and the catchability coefficient is $q = 2.5 \cdot 10^{-4}$ per vessel-year, with unit of time equal to one year. The price of fish is constant (across volume and size of fish), p = 2.00 \$/kg, and cost per vessel-year is a = 0.5 million \$.

1. What is F when E = 4000 vessel-years?
2. Use figure 8.5 to sketch the corresponding graphs of eumetric revenue and total cost of fishing mortality (tip: see figure 8.6 and use cost per unit F, $c = TC/F$, to draw the total cost of fishing mortality curve, $C(F) = cF$).
3. Use the graphs to find approximate values for F_{∞}^{EU}, F_{∞}^{3}, F_{∞}^{0} and F_{MEY}. What are the corresponding number of vessels?

9 MULTISPECIES AND ECOSYSTEM HARVESTING

This chapter will introduce some important concepts and models being used in economic analysis of multispecies and ecosystem harvesting. We shall focus on predator-prey interactions that are a key to the understanding of more complex aquatic ecosystems and models of such systems.

A classic on multisp ecies management:

> *The amount of food for each species of course gives the extreme limit to which each can increase; but very frequently it is not the obtaining food, but the serving as prey to other animals which determines the average number of a species. Thus, there seems to be little doubt that the stock of partridges, grouse and hares on any large estate depends chiefly on the destruction of vermin. If not one head of game were shot during the next twenty years in England, and, at the same time, if no vermin were destroyed, there would, in*

all probability, be less game than at present, although hundreds of thousands of game animals are now annually shot. (Darwin, 1882, pp. 53–54; quoted from Volterra, 1928, pp. 21–22.)

9.1 MULTISPECIES AND ECOSYSTEM MANAGEMENT

The purpose of this section is to introduce the reader to bioeconomic multispecies modelling and management. We shall do so by use of simple graphical analysis and examples from North Atlantic fisheries. The mathematical tool for deriving one of the key graphs is known to most students and will be used in the next section.

Each fish stock is a part of a greater ecosystem, interacting with its prey, predator and competitor species, in addition to being affected by other biological as well as physical conditions in the sea. A typical fish species targeted by man both consumes some species and serves as prey for others. Who eats whom may also vary on a temporal and spatial scale. For example, big adult fish may feed even on their own offspring in addition to prey where the individual fish is small. As the offspring grows bigger, individuals change from serving as feed to become predators on the next generation of offspring. Such cannibalistic behaviour is also an important part of many fish communities, including for cod (*Gadus morhua*) and herring (*Clupea harrengus*) in the North Atlantic. Marine ecosystems may be more or less complex and the number of commercially exploited species varies. In general, tropical systems seem to be richer in number of species than ecosystems in the temperate zones. For example, the Mekong river ecosystem has around 1400 species of fish and crustaceans whereas the Barents Sea ecosystem in the Northeast Atlantic has only a tenth of this.

Box 9.1 Hippopotamus management in the old Egypt

If we can trust the historic portrayal of the novel *River God* (Wilbur Smith, 1993) the old Egyptians managed actively their aquatic resources nearly 3800 years ago, in the 1790s BC under the reign of Queen Lostris.

The priests of Hapi had kept a strict count of the number of these great beasts in the lagoon, and had given sanction for fifty of them to be slaughtered for the coming festival of Osiris. This would leave almost three hundred of the goddess's flock remaining in the temple lagoon, a number that the priests considered ideal to keep the waterways free for choking weed, to prevent the papyrus beds from encroaching upon the arable lands and to provide a regular supply of meat for the temple. Only the priests themselves were allowed to eat the flesh of the hippopotamus outside the ten days of the festival of Osiris.
"River God", p. 9.

Co-evolved species adapted to their environment may have complex dynamics that are difficult to fully comprehend. For biologists and other natural scientists there is hardly any limit to how much research is needed to describe and predict further development of each species, commercial or non-commercial, in its ecosystem. Nevertheless, for management of any single species or multispecies, objectives setting harvest quotas, limiting effort, collecting resource taxes and imposing technical restrictions are among the policy means available. A key question when it comes to ecosystem management is how much of the complex dynamics of nature do we have to know to manage those species we want to harvest or to protect from harvesting? Management costs are not negligible, in particular when it comes to ecosystem or multispecies research and management. For actual management, cost-benefit analysis of such approaches should be warranted.

9.1.1 EFFORT AND STOCK LEVELS

The main results of single species bioeconomic analyses are that the optimal level of fishing effort is less than the open-access level and that the optimal stock level is higher than the open-access level. These general results are valid whether the optimum is derived by maximising annual economic rent or the present value of all future rent. For static rent maximisation the main results of single species analysis are shown in Figure 9.1. Panels (a) and (b) show how the sustainable revenue and the total cost of harvesting vary with fishing effort and stock level, respectively. Generally speaking, the optimal level of fishing effort, E^*_{ss}, is less than the open access level, E^{oa}_{ss}, and the optimal stock level, X^*_{ss}, is higher than the open access level, X^{oa}_{ss}. These general results are valid whether the optimum is derived by maximising annual economic rent or the present value of rent.

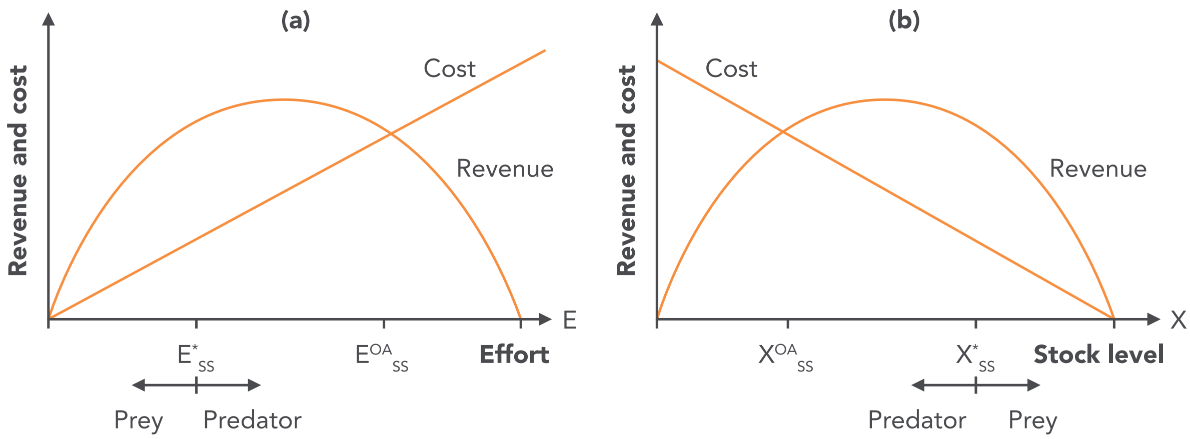


Figure 9.1. Open access (OA) and optimal (*) effort (*E*) and stock level (*X*) in a single species (SS) model. Arrows indicate the most likely direction of change of optimal *E* and *X* if the stock is a prey or a predator, respectively.

In single species models, the biological constraint to the optimisation problem is the yield-effort or yield-stock curves on which the revenue curves are based. Moving from single species to two species models, changes the biological constraint to, for example, the maximum sustainable yield frontier (MSF), shown in Figure 9.2. The MSF is derived (see the next sub-chapter, 9.2) by maximizing yield of species no.2 for a given yield of species no.1 when there are biological interactions between the two species. Maximising yield from each of the two species as if it were independent of the other, gives the combined yields at the point S in Figure 9.2. However, this is not a sustainable combination of yields since it is outside the MSF. Any point on or inside the MSF would be sustainable (see e.g. Flaaten, 1988 and 1991).

What combination of yield should be chosen depends in general on the management objective, as well as the price of fish and the harvest cost for each species.[25] In the biology literature, objectives for managing fish stocks are usually related to the maximum sustainable yield (MSY), yield per recruit (Y/R) or some related concepts. In cases of two or more biologically interdependent species, maximum sustainable yield frontiers (MSF) might replace the single-species MSY concept. However, the fallacy of biological management objectives is that they do not consider the economic benefits and costs of fisheries. Many fish stocks are deliberately not fished due to low market price and/or high catch cost. In the Barents Sea, for example, there are more than 100 fish species, but only about 10 are commercially targeted.

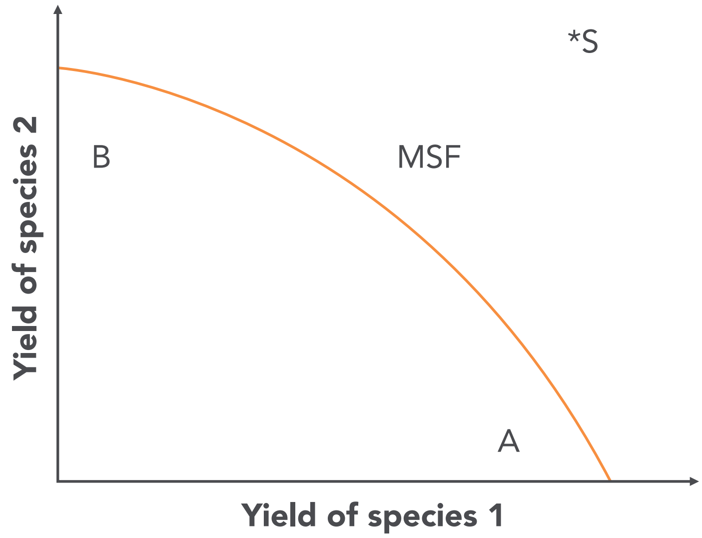


Figure 9.2. The maximum sustainable yield frontier (MSF) gives the maximum possible yield of one species for a given yield of the other.

Some international organisations and agreements have established their own objectives for fisheries management. The Food and Agriculture Organization of the United Nations (FAO) formulated the following objective (see Box 4.1):

> *Recognizing that long-term sustainable use of fisheries resources is the overriding objective of conservation and management, states and subregional or regional fisheries management organizations and arrangements should, inter alia, adopt appropriate measures, based on the best scientific evidence available, which are designed to maintain or restore stocks at levels capable of producing maximum sustainable yield, as qualified by relevant environmental and economic factors, including the special requirements of developing countries.* (FAO, 1995.)

Thus, even though the FAO's Code of Conduct establishes the single-species concept, with maximum sustainable yield as the main management objective, it is qualified by relevant environmental and economic factors.

Contrary to the management objectives above, economic objectives are strongly related to social welfare theory that emphasises the net economic results to society of utilising natural resources. "Society" in this context usually means a country, but it could also mean a group of indigenous people, a region within a country, or a group of countries. The resource rent is the gross catch value minus the harvest costs. If stocks are jointly managed, the objective could be to maximise the combined resource rent, or the present value of all future rent from them. With respect to the effect that the relative net value of harvest has on the optimal combined harvesting, let us use two simplified examples to illustrate this. In both cases we assume that there are predator-prey interactions between the stocks and that they can be harvested independently of each other.

Example 1. Valuable predator and cheap prey

Let species 2 be a predator of high net value per unit harvest and species 1 a low net valued prey species. In this case the optimal combined yield is in the vicinity of B in figure 9.2 where the prey is mainly kept in the sea as feed for the predator. In this case the effort of the predator fishery does not have to be increased (much) compared with its single species effort shown in figure 9.1(a), whereas the effort of the prey fishery should be decreased. The effects on the stock levels are opposite to the effects on the effort levels.

Example 2. Predator of low net value and prey of high net value

If the predator is of low market value and/or expensive to harvest, its net value per unit harvest is low. Likewise, if the prey is of high market value and/or cheap to harvest its net value per unit harvest is high. In this case the optimal combined harvest is in the vicinity of A in figure 9.2 where the predator stock is fished down to leave more prey to be harvested by the fishermen. In some cases it even pays to subsidise the fishermen to harvest more predators than they otherwise would have done. In this case the optimal effort of the predator fishery should be increased and the stock level of the predator reduced compared with the single species case, as indicated by the arrows in figure 9.1.

Non-consumptive values of certain species of a marine ecosystem should also be included in a complete analysis, if such values are considered significant. The international discourse on, inter alia, whaling, sealing, dolphin by-catch and turtle excluder devices demonstrates the importance of integrating non-consumptive issues in the management objectives. Further analysis usually reveals the need for a trade-off between use (harvest) and non-use (protection) values, even more so when the non-use values are connected to top-predators that consume commercially valuable fish.

9.1.2 MIXED CATCH AND GEAR SELECTIVITY

In most fisheries catches consist of more than just the main targeted species. Mixed catches create other management problems in addition to the ones discussed above. This is especially the case when the catch consists of species of different size distribution and with different growth properties. The mixed catches of, inter alia, cod, haddock and whiting in the North Sea trawl fishery is an example of this. Figure 9.3 illustrates this problem. One particular type of gear may use either a small or a large mesh size in the net to catch two species simultaneously. The small mesh size gives MSF_A whereas the big mesh size gives MSF_B in figure 9.3.

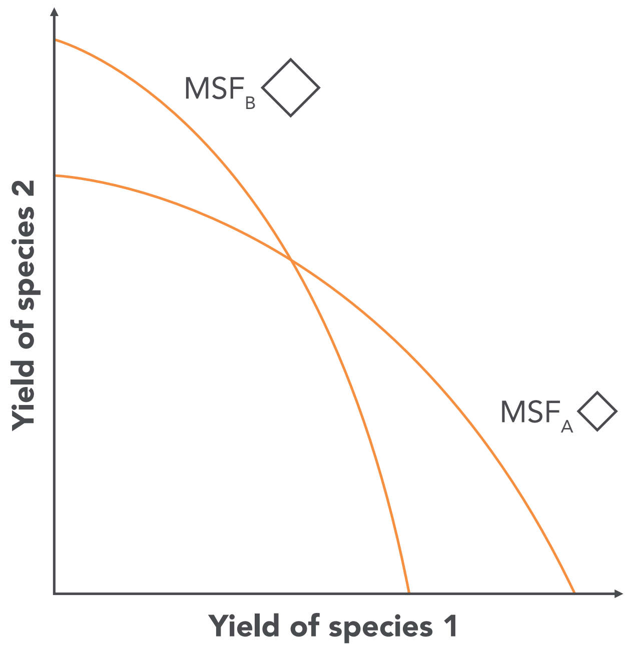


Figure 9.3. The maximum sustainable yield frontier (MSF) in mixed fisheries may depend on the mesh size of the nets. A indicates MSF for small mesh size and B for big mesh size.

Species 1 may consist of plentiful small fish that easily escape gear with big meshes. Species 2 has fewer but bigger fish that are fished too young when small meshed nets are used. What combination of yield should be chosen depends in general on the management objective and on the ratio of cost of effort-price of fish between the two stocks. If the stocks are jointly managed, the objective could be to maximise the combined resource rent from them. Another solution would be to try to develop selective gear and fishing methods to avoid mixed fisheries.

After this brief and simple presentation of some results from bioeconomic single and multispecies theory, I will now give a few examples of modelling and management of North Atlantic fisheries and try to relate this to the theory.

9.1.3 EXAMPLES FROM THE NORTH ATLANTIC

For many years, biologists and other scientists in the North Atlantic coastal states have undertaken research on marine multispecies interactions. There are also examples of bioeconomic multispecies analyses of fisheries in these areas (see, e.g., Eide and Flaaten, 1998). Russian and Norwegian researchers have conducted studies on "who eats whom" in the Barents Sea area and have modelled these multispecies interactions (see e.g. Rødseth, 1998). Two figures will give an example of why it may be important to also include economic aspects in multispecies modelling, instead of relying on biological reasoning only. Figure 9.4 shows the Northeast Atlantic cod's age-dependent average annual consumption of some commercially important prey species. Species included are shrimp, capelin, herring and cod (cannibalism) above 5, 10, 10 and 20 cm, respectively. The figures are in grams of prey per kg of cod, for each age class of cod from 1 to 7+ years. Figure 9.4 shows, for example, that 1 kg of two-year-old cod annually consumed 2000 grams of prey of these four species above the given size, and that about 75 per cent of this was capelin. For all age classes, capelin is the main prey among the species and size groups included in figure 9.4.

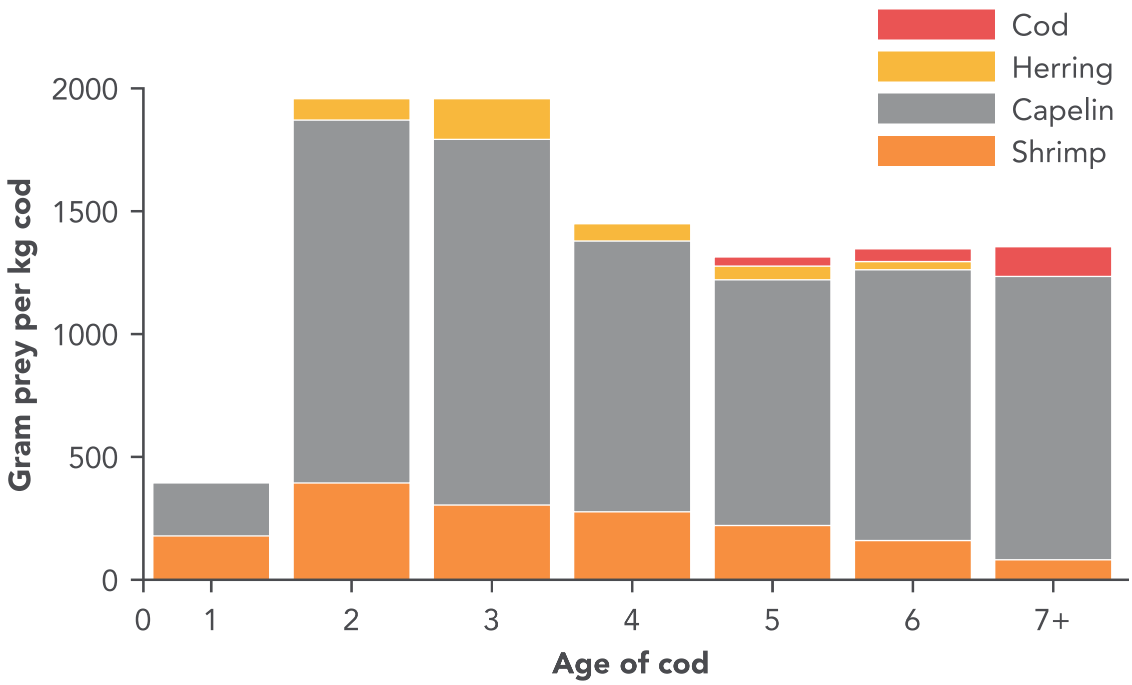


Figure 9.4. Arcto-Norwegian cod's age-dependent average annual consumption of some commercially important prey species. Species included are shrimp (*Pandalus borealis*), capelin (*Mallotus villosus*), herring (*Clupea harengus*) and cod (*Gadus morhua*) above 5, 10, 10 and 20 cm, respectively. In grams of prey per kg of cod, 1984–92. Calculations based on data from The Institute of Marine Research, Bergen.

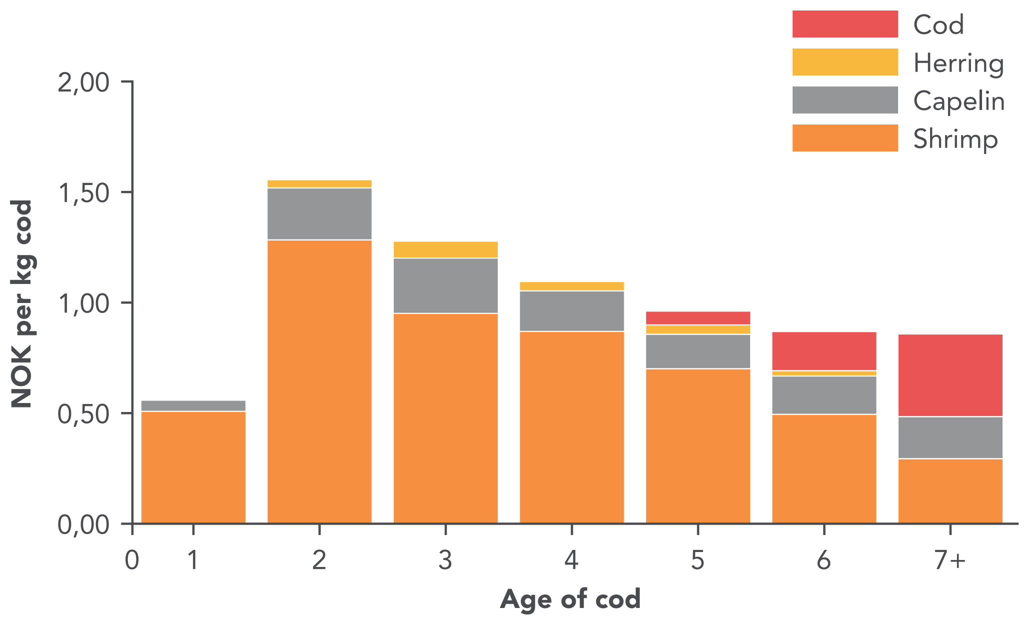


Figure 9.5. Age-dependent average annual opportunity cost of Arcto-Norwegian cod's consumption of some commercially important prey species. Species included are shrimp (*Pandalus borealis*), capelin (*Mallotus villosus*), herring (*Clupea harengus*) and cod (*Gadus morhua*) above 5, 10, 10 and 20 cm, respectively. In NOK per kg of cod, in 1991–92 prices. Consumption data from 1984 to 1992.
Sources: Calculations based on biological data from the Institute of Marine Research, Bergen, and economic data from The Directorate of Fisheries, Bergen.

Taking the net opportunity cost of feed into consideration (see Flaaten and Kolsvik, 1995, for details) gives the results shown in figure 9.5. The net value of the prey is the net contribution that the fish in the sea could have given for the prey harvesters if they had less competition from the predator, the cod. The net value per unit of catch was found by Flaaten and Kolsvik (1995) to be 30 per cent of the quay-side price in these fisheries. In other words, if a predator eats fish that would have been worth € 1.00 at the quay, the fisher's net loss is only € 0.30 since he would have had to spend € 0.70, including labour costs, to catch the fish. Figure 9.5 shows, for example, that two-year-old cod had an annual feed cost of NOK 1.50 (€ 0.20) per kg of biomass, and that about 75 per cent of this was inflicted on the shrimp fisheries. Except for age class 7+, the opportunity cost of shrimp dominates the economic figures, whereas capelin dominated the biological results in figure 9.4.

The model MULTSPEC from the Institute of Marine Research (IMR), Bergen (see Tjelmeland and Bogstad, 1998) is a biological multispecies model for the Barents Sea fish/sea-mammal system. The MULTSPEC model includes cod, capelin, herring, minke whale (*Balaenoptera acutorostrata*), harp seal (*Pagophilus groenlandicus*) and species of zooplankton. The ECONMULT model (see Eide and Flaaten, 1998) is a bioeconomic multifleet model to be used with more aggregated multispecies models than the very detailed MULTSPEC. MULTSIMP and AGGMULT are aggregated models (see Tjelmeland, 1990 and 1992; Eide and Flaaten, 1998). None of these models include shrimp, even though figures 9.4 and 9.5 indicate that shrimp should be included in the bioeconomic multispecies analysis of the Barents Sea fisheries.

9.1.4 INTERACTIONS OF FISH AND SEA MAMMALS

Some species of whales and seals are important predators on fish in the North Atlantic. Icelandic, Norwegian and other scientists have for many years conducted research on the feeding ecology of whales and seals. Sigurjónsson and Vikingsson (1995) give an excellent review of much of the work done on whales, dolphins and porpoises in the area between Greenland, Iceland, Jan Mayen and the Faroe Islands until the mid 1990s (also see Sigurjónsson and Vikingsson, 1997). Their report also gives estimates, using two different methods, of annual consumption by these species in different parts of this area. On average, the consumption of commercially valuable fish is about 25 per cent of the total annual feed of whales. The total fish consumption exceeds 1.2 million tonnes per year in Icelandic and adjacent waters (mid 1990s). With regard to the implications for management of their results, Sigurjonsson and Vikingsson are careful with their conclusion:

> *The present analysis of consumption…is just one step towards a better understanding of the role of cetaceans in the marine ecosystem in these waters. The results show, however,*

> *that the amount of food consumed is substantial, while the implications of that conclusion require further study.* (Sigurjónsson and Vikingsson, 1995 p. 10).

For the Barents Sea and parts of the Norwegian Sea the paper by Schweder et al. (1998) investigates the effects on cod and herring fisheries of changing the target stock level of minke whales. Using a scenario modelling approach the biological model includes cod, herring, capelin and minke whales – with fish populations age and length distributed and minke whales age and sex distributed. The minke whale is an opportunistic forager that consumes plankton and other fish in addition to cod, herring and capelin. One of the findings is that a reduction of the minke whale stock from 72 per cent of carrying capacity to 60 per cent increases the annual catch of cod by some 100 thousand tonnes. This corresponds to an increase in the annual catch of cod by approximately 6 tonnes with a mean reduction in the whale stock of one animal. For herring no clear main effect was found on catch, due to the biological interactions between species and size groups. With respect to implications for fisheries management the authors conclude:

> *The results concerning the effects on the cod and herring fisheries must be taken as tentative since the ecosystem model used could be improved, and so could the strategies for managing the fisheries.* (Schweder et al., 1998 p. 77).

When it comes to predators like whales and seals, however, harvesting is often controversial, as the following quotation demonstrates:

> *An early exploration (of multispecies fisheries), May et al. (1979), has proved very influential, and now forms the basis for a very controversial piece of work, a bioeconomical analysis of the Barents Sea fishery by Flaaten (1988). Flaaten's work is controversial because of his conclusion that sea mammals should be heavily depleted to increase the surplus production of fish resources for man.* (Yodzis, 1994, p. 51.)

Harvesting is, however, not the only utility generated from sea mammals. It has long been acknowledged that non-use values included in the objective function may have implications for stock management. The following quotation demonstrates this:

> *It should, however, be stressed that this result* [*…that the sea mammals should be heavily depleted to increase the surplus production of fish resources for man…*] *may be somewhat modified if the resource is assigned an optional value from people's willingness to pay for keeping the stock at higher level. A biological argument that also may weaken our result is the eventual existence of critical depensation for lower stock levels.* (Flaaten, 1988, p. 114.)

An alternative to comprehensive multispecies or ecosystem models is partial analysis. Flaaten and Stollery (1996) developed methods for the calculation of the net cost that predators inflicted upon the prey species fisheries. Applying one of the methods to the Northeast Atlantic stock of minke whales[26] predation of fish, we estimated the annual predation costs per minke whale, at 1991–92 prices, at between NOK 11,600 and NOK 15,100. This would amount to between approximately USD 2,340 and USD 3,040 per minke whale using 2017 prices and exchange rates.

9.1.5 AN HISTORICAL NOTE

The examples I have given on multispecies modelling so far are all from the North Atlantic. The reason for this is simple – this is the area where I am working and that I know pretty well. There are, however, several examples of especially biological multispecies modelling of fisheries in other parts of the world. My final example is from the Mediterranean, and this is not just an ordinary example, but one of the most important ones in the history of multispecies modelling and management.

The first ever attempt, as far as I know, at conducting a multispecies analysis of fishing was by means of limit cycle models. Empirical studies of the Upper Adriatic Sea fisheries before, during and after the First World War found in D'Ancona (1926) were an important source of inspiration to the theoretical works by V. Volterra (1928) as demonstrated by this quotation:

> *Doctor UMBERTO D'ANCONA (D'Ancona, 1926) has many times spoken to me about the statistics which he was making in fishery in the period during the war and in periods before and after, asking me if it were possible to give a mathematical explanation of the results which he was getting in the percentages of the various species in these different periods. This request has spurred me to formulate the problem and solve it, establishing the laws which are set forth in § 7. Both D'Ancona and I working independently were equally satisfied in comparing results which were revealed to us separately by calculus and by observation, as these results were in accord; showing for instance that man in fisheries, by disturbing the natural condition of proportion of two species, one of which feeds upon the other, causes diminution in the quantity of the species that eats the other, and an increase in the species fed upon.* (Volterra, 1928, p. 4).

Based upon his empirical studies of the fisheries of the Upper Adriatic Sea, D'Ancona (1926) concluded that the predators of this sea, the sharks, ought to be decreased by increased harvest intensity. That would make it possible to increase the yields of more valuable prey stocks.

Hopefully, this section has shown that in some cases, at least, multispecies modelling is useful, if not necessary, for improved overall management. This is especially so when there are strong predator-prey or competitive biological interactions among species that can be harvested independently of each other. A biological multispecies model gives the biological restriction on the possible combinations of harvest rates for the species in a particular area. In addition, a bioeconomic multispecies model helps to pick the optimal combination of harvest rates. Multispecies models may also help understanding variations over time in catch and effort composition, as seen in the case of the Upper Adriatic Sea before, during and after the First World War.

9.2 MORE ON PREDATOR-PREY MODELLING

We shall in this section give a review of a two-species predator-prey model and derive its maximum sustainable yield frontier (MSF), analysed in May et al. (1979) and Flaaten (1986). Suppose there is a prey, W_1, on which the existence of a predator, W_2, is based. W_1 and W_2 can be thought of as biomasses. A simple model describing the dynamics of such a system is

$$\dot{W}_1 = dW_1/dt = r_1W_1(1 - W_1/K) - aW_1W_2 \quad (9.1)$$

$$\dot{W}_2 = dW_2/dt = r_2W_2(1 - W_2/\alpha W_1)\ , \quad (9.2)$$

where r_1 and r_2 are the intrinsic growth rates of the respective species. K is the carrying capacity of the total systems, at which the prey will settle in the case of no predator and no harvest.

The per capita[27] growth rate of the prey decreases from r_1 for stock levels close to zero, to zero for stock levels equal to the carrying capacity in case of no predators. If predators exist, the per capita growth rate for the prey becomes zero for a stock level lower than its carrying capacity. The presence of predators reduces the per capita growth rate in proportion to the biomass of the predator. The predation coefficient, a, tells how much the per capita growth rate of the prey reduces per unit of the predator, or to put it another way, a tells which share of the prey stock one unit of the predator is consuming per unit of time. The total rate of consumption is expressed in the term of aW_1W_2. Note that the predator's consumption is similar to fishermen's harvest in the Schaefer harvest function discussed in Chapter 3.

The predator's per capita growth rate decreases from r_2 when its own stock level is close to zero, to zero for a stock level equal to its own carrying capacity, which is proportional to the level of the prey stock. The proportionality coefficient α is the equilibrium stock ratio.

Mathematical stability properties of the model (9.1)–(9.2) will not be discussed here. (It can be found in the literature of theoretical ecology, e.g., in Beddington and Cook (1982), May (1974) and May (1981), as well in mathematics texts for economists, e.g., Sydsæter et al. (2008).) However, it is easy to see, by letting $\dot{W}_1$ and $\dot{W}_2$ equal to zero in (9.1) and (9.2), that if an equilibrium point exists with both species being positive, the stock levels will be[28]

$$W_1 = \frac{K}{1+\nu}\ , \quad (9.3)$$

$$W_2 = \frac{\alpha K}{1+\nu}\ , \quad (9.4)$$

where $\nu = a\alpha K/r_1$.

It should be noticed that the intrinsic growth rate of the predator, r_2, does not affect the equilibrium values of either of the two species. The equilibrium values of both species increase with any increase in r_1 or K, ceteris paribus. From (9.3) and (9.4) it follows

$$W_2/W_1 = \alpha\ . \quad (9.5)$$

The equilibrium stock ratio α determines the relative size of the predator stock to that of its prey, when there is no harvesting. Outside equilibrium the relative stock size differ from α except for along the predator isocline.

Even though r_2 does not affect the equilibrium values of the stocks, it is of importance to the behaviour of the system outside equilibrium. Defining the "natural return time", T^R, of the species as

$$T_i^R = 1/r_i \qquad i = 1,2 \ , \tag{9.6}$$

r_2 will affect the time the predator will need to reach equilibrium from a higher or lower level.

Suppose that the fish stocks are harvested independently with constant effort per unit of time, F_i, scaled such that $F_1 = 1$ corresponds to constant catchability coefficients equal to r_i. Then the catch rates will be

$$h_1 = r_1 F_1 W_1 \tag{9.7}$$

$$h_2 = r_2 F_2 W_2 \ . \tag{9.8}$$

With harvesting introduced this will influence the growth rates in (9.1) and (9.2).

To simplify notation and the analysis a little we define the dimensionless stock levels $X_1 = W_1/K$ and $X_2 = W_2/\alpha K$. Then rewrite equations (9.1) and (9.2) as

$$dX_1/dt = r_1 X_1(1 - F_1 - X_1 - \nu X_2) \tag{9.9}$$

$$dX_2/dt = r_2 X_2(1 - F_2 - X_2/X_1) \tag{9.10}$$

when harvesting, $y_1 = r_1 F_1 X_1$ and $y_2 = r_2 F_2 X_2$, is included. Here the dimensionless parameter ν is defined as $\nu = a\alpha K/r_1$.

The equilibrium properties of this ecological system depend only on the fishing efforts, F_1 and F_2, and ν. The dynamics additionally involve r_1 and r_2. The phase-diagram for the system (9.13)-(9.14) is shown in Figure 9.6. The isoclines are found by setting $dX_1/dt = 0$ and $dX_2/dt = 0$ in (9.9) and (9.10). This gives

$$X_2 = (1/\nu)(1 - F_1 - X_1) \text{ for } dX_1/dt = 0 \tag{9.11}$$

$$X_2 = (1 - F_2)X_1 \text{ for } dX_2/dt = 0 \;. \tag{9.12}$$

If positive equilibrium values of X_1 and X_2 exist simultaneously they are found where the isoclines intersect, that is for

$$X_1 = \frac{1 - F_1}{1 + \nu(1 - F_2)} \tag{9.13}$$

$$X_2 = \frac{(1 - F_1)(1 - F_2)}{1 + \nu(1 - F_2)} \;. \tag{9.14}$$

X_1 and X_2 both equal $1/(1 + \nu)$ in the absence of fishing, and zero in the case of F_1 = 1. In addition, X_2 will equal zero if F_2 = 1. Thus there is a limit to how intensive fishing can be without causing extinction of the stocks. With fishing the relative stock size is $X_2/X_1 = 1 - F_2$.

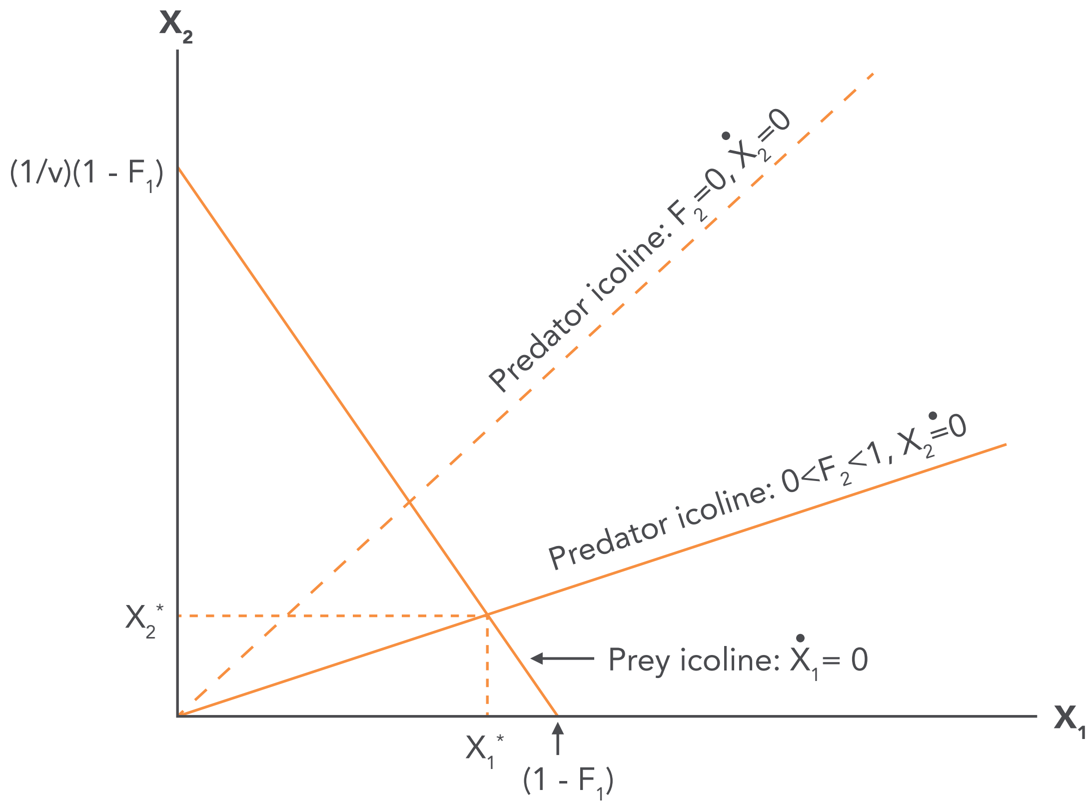


Figure 9.6. Phase diagram for a predator-prey model.

It is seen from (9.13) that only for $F_1 < 1$ will there exist a positive equilibrium value of the prey. If $F_1 \geq 1$ the prey-stock will be extinct, and so, of course, will be the predator, as seen from (9.14). The latter expression shows that only for $F_2 < 1$ and $F_1 < 1$ will the predator survive.

The equilibrium values of both species increase with decreasing fishing pressure on the prey, i.e., for reduced F_1. More of the prey gives increased carrying capacity for the predator which can be kept on a higher level.

On the other hand, the effects on the prey and the predator from decreased fishing pressure on the predator are the opposite of each other. From (9.13) it is seen that the equilibrium value of the prey will decrease, and from (9.14) that the predator will increase. The increased stock level of the predator means heavier predation on the prey, and thereby a reduced equilibrium level for the latter.

Let us now investigate the MSF for this two-species model. It may be of interest from both a biological and an economical efficiency point of view to maximise the sustainable yield of one species for a specified constant sustainable yield level of the other. This problem is equivalent to that of welfare economics: deriving the production possibility frontier by maximising the output of one good for a specified amount of output of the other, for a fixed amount of factors of production. In the two-species biological system the limited amount of factors of production are embodied in the carrying capacity and the intrinsic growth rate of the model. In a marine ecosystem, the limited factor of production used for "production" of fish will usually be the zoo-plankton communities.

The problem of maximising

$$y_1 = r_1 X_1 (1 - X_1 - \nu X_2) \tag{9.15}$$

subject to the constraint

$$y_2 = r_2 X_2 (1 - X_2 / X_1) = \text{constant}, \tag{9.16}$$

can be done by using the Lagrange method (see Box 6.1), as demonstrated in Beddington and May (1980).

The Lagrangian function of this problem is

$$L(X_1, X_2) = r_1 X_1 (1 - X_1 - \nu X_2) - \lambda (r_2 X_2 (1 - X_2 / X_1) - y_2). \tag{9.17}$$

We shall use the first order conditions for the solution of the problem, and they are

$$\frac{\partial L(X_1,X_2)}{\partial X_1} = r_1 - 2r_1X_1 - r_1\nu X_2 - \frac{\lambda r_2 X_2^2}{X_1^2} = 0 \tag{9.18}$$

$$\frac{\partial L(X_1,X_2)}{\partial X_2} = -r_1\nu X_1 - \lambda r_2 + \frac{2\lambda r_2 X_2}{X_1} = 0\ . \tag{9.19}$$

To eliminate λ we first rearrange equations (9.18) and (9.19) and get

$$\lambda = \frac{X_1^2(r_1 - 2r_1X_1 - r_1\nu X_2)}{r_2X_2^2} \tag{9.20}$$

$$\lambda = \frac{-r_1\nu X_1}{r_2(1-\frac{2X_2}{X_1})}\ . \tag{9.21}$$

From equations (9.20) and (9.21) we eliminate λ and derive the following quadratic equation:

$$2X_1^2 - (1+(4-\nu)X_2)X_1 + X_2(2-3\nu X_2) = 0\ , \tag{9.22}$$

which has the following two solutions for X_1 for given values of X_2:

$$X_1^{1,2} = \frac{1}{4}(1+(4-\nu)X_2) \pm \frac{1}{4}\left[(1+(4-\nu)X_2)^2 - 8X_2(2-3\nu X_2)\right]^{1/2} \tag{9.23}$$

For each level of X_2 we calculate X_1 from (9.23), and the resulting yields, y_1 and y_2, are given by (9.15) and (9.16). The locus combining the yields of the two species is shown in figure 9.7 for ν = 2. This is the maximum sustainable yield frontier (MSF), named so to emphasise the connections to the concepts used in welfare economics. MSF gives the absolute sustainable yield of either population for a specified yield of the other. All combinations of yields on or below this curve are sustainable, whereas yields to the northeast of the curve are possible for some period of time, but they are not sustainable. The star in the northeast corner corresponds to a combination of the largest possible yield of the prey and the largest possible yield of the predator, but such a combination of yields is definitely not sustainable.

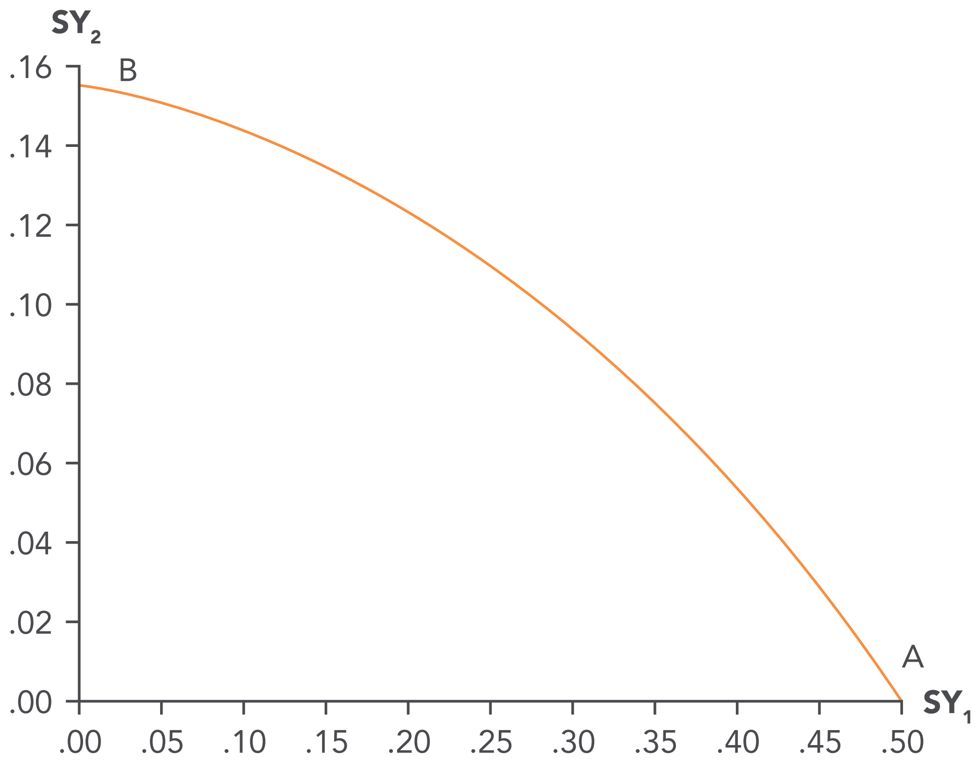


Figure 9.7. The maximum sustainable yield frontier (MSF) of a two-species model shows sustainable combinations of yield of species 1 (SY_1) and species 2 (SY_2). Parameters used are r_1 = 2.0, r_2 = 1.15 and v = 2.0.
Source: Flaaten (1988).

From the single species logistic growth model it is known that a given sustainable yield less than the maximum sustainable yield (MSY) can be harvested at two different stock levels, above or below the MSY level. These two ways of harvesting are called biological underexploitation and overexploitation, respectively. From a biological point of view the best way of harvesting is to harvest the MSY, whereas the economical optimal yield stock level, also depend on product price, harvesting cost and discount rate in addition to biological factors.

Unit harvesting cost is usually assumed to be a decreasing function of stock level, leading to the conclusion that the resource should be biologically underexploited to reduce costs. On the other hand, a positive discount rate leads to the conclusion that the resource should be heavily exploited since a given amount of net revenue "today" is preferred to the same amount "tomorrow". In other words, from an economic point of view, harvesting below, at or above the MSY stock level can all be optimal; it is a question of prices, costs and discount rates (see Chapter 4).

The smallest of the two solutions of equation (9.23) corresponds to a biologically inefficient harvest level, either underexploitation of the predator, or overexploitation of the prey. In the former case the predator is kept on the highest stock level of two possible ones, both giving the same sustainable yield of the predator. A higher predator stock means more consumption of the prey, thereby removing a potential prey yield. To achieve the highest possible sustainable yield of the prey for a given predator yield it is therefore obviously best to underexploit the predator. For similar reasons it is efficient to underexploit the prey to give more food to the predator. MSF harvesting thus means that the predator shall not be underexploited, and neither shall the prey be overexploited.

The terminal points of the MSF locus in figure 9.7, A and B, are related to specific stock levels of the predator and the prey. At point A the predator is extinct and the prey is at its single species biological optimum level:

$$X_1|_{X_2=y_2=0} = 1/2 \ . \tag{9.24}$$

The absolute maximum sustainable yield of the predator, at point B in figure 9.7, occurs for an unharvested prey stock above, at or below its single species biological optimum, depending on the size of the dimensionless combination of parameters, ν. The smaller ν is, the higher will be the prey stock level. In fact it can be shown that

$$X_1|_{F_1=y_1=0} \underset{<}{\geq} 1/2 \qquad \text{if} \qquad \nu \underset{>}{\leq} 3 . \tag{9.25}$$

At point B in Figure 9.7 there is no prey harvest and this entire species is left in the sea as natural feed for the predator.

From the definition of υ we know that it will be smaller the lower the predation coefficient a and the equilibrium stock ratio α. In other words, the maximum stock level of the prey is greater the lower the predator pressure, which is in accordance with the quotation from Charles Darwin at the beginning of this chapter.

The maximum sustainable yield frontier (MSF) in Figure 9.7 pinpoints a key management issue for the case of multispecies harvesting. Should we aim at harvesting mainly then predator species and leave the prey in the sea as feed for the predators? Or should we mainly aim at harvesting the prey, by fishing down the predators? The latter would imply biological overfishing of the predator. Such questions are important in many of the world's fisheries, including the krill-sea mammals system in the Antarctica, the fish-fish-sea mammals system in the Northeast Atlantic and the fish-sea mammals system in the North Pacific. When it comes to in particular sea mammals the issue of non-consumptive value of charismatic species brings an additional dimension into management that we have not explored in this chapter (see e.g. Bulte and Von Kooten, 1999).

Exercise 9.1

1) Assume the following two species interaction:

$$\frac{dX_1}{dt} = r_1 X_1 \left(1 - \frac{X_1}{K}\right)$$

$$\frac{dX_2}{dt} = r_2 X_2 \left(1 - \frac{X_2}{aX_1}\right)$$

a) Formulate a simple predator–prey model (put in missing segments in the above equations) with harvesting, and draw the isoclines in a phase plane diagram.
b) Explain what happens to stock levels and harvest when the harvest of the predator is increased.
c) Explain how you would manage this fishery if the predator has no value in the market.

10 RECREATIONAL FISHING

This chapter discusses recreational fishing, where people (consumers) are willing to pay to go fishing. The willingness to pay may depend on several environmental and resource characteristics. We focus on the demand for fishing days and quality and analyse the open-access, the competitive and the social optimal recreational fishery.

10.1 RECREATIONAL ANGLING

Recreational fishing is fishing for fun. The view of what is fun in life differs from person to person, and some people do not think fishing is fun at all. Thus there are at the same time and in the same country some who participate in recreational fishing and some who do not. The fun usually depends on several characteristics of the fishing itself and on other amenities. The size of individual fish, the size of the catch per day fishing, the fishing process itself, the fish species available and the natural scenery at the fishing spot are among the characteristics recreational fishermen consider when contemplating whether to go fishing or not. Travel time and out-of-pocket costs matter. Of course income and the cost of fishing also matter for the demand for recreational fishing as for other goods and services, and we may, at the market level, analyse this good as we do for other goods. However, at the individual level the recreational fishing good is often a discrete good that is available only in integer units, for example when you have to buy fishing permits only for full days' fishing (e.g. $/day).

Other terms used for recreational fishing include sport fishing and hobby fishing. We shall, however, use recreational fishing and distinguish this from the commercial fishing and small-scale fishing discussed in the previous parts of this book, where the market value of the catch is balanced against the costs of the commercial firm or the opportunity costs of the small-scale fisherman. A person who takes part in recreational fishing will in this chapter be called an angler, since in most cases recreational fishing is conducted by use of hook and line. To fish for fun requires that people have earned income in other activities to spend on goods and services, including on recreational fishing. In actual cases we may find fishermen who combine recreational fishing with subsistence fishing to gain food for the household and/or small-scale commercial fishing to obtain cash. Here, however, we shall focus on recreational fishing proper.

From an economic point of view recreational fisheries may be treated as any other good that gives utility for the consumers and resource owners. However, the fish in the water is a common pool resource implying that any catch of one recreational fisherman has an effect on the stock, thereby reducing the harvest potential for the other recreational fishermen.

In this respect recreational fisheries share the externalities characteristic of the commercial fisheries discussed in the previous chapters. Consumers choose to buy or not to buy a good, and if they buy they also have to decide on the quantity. Thus, for recreational fishing as a consumer good, we may ask who the fishermen are, what species and how much they catch, how they catch (gear type), where they go fishing and at what time or season.

Why should we from an economic point of view be interested in recreational fisheries? Is this not just a minor hobby activity for a few people? Like fisheries discussed in the previous chapters, also recreational fisheries demonstrate externalities. These require management for at least three reasons. First, recreational fishing is a popular activity that gives fun, pleasure and exercise to lots of people. Globally recreational fisheries are a big and still increasing part of fisheries. In some countries they are even bigger than the commercial fisheries sector if we compare expenditures in recreational fisheries with the landing value in the commercial sector (see articles in Aas, 2008). In a recent survey of seven developed countries' recreational fisheries, participation rates varied from five (Germany) to fifty-five (Lithuania) per cent of the total population. Finland and Sweden both had a participation rate of more than thirty per cent (Ditton, 2008). Considering that some people are too young or too old to go fishing, these numbers indicate that recreational fishing is a widespread spare-time activity. Of course some people fish only once a year, but others fish regularly. Second, in some areas there are increasing conflicts between commercial and recreational fishing. As the commercial sector is more and more restricted in its activities, it is also natural to look into recreational fishing and its effects on resources in the commercial sector to minimize conflicts and to increase the total social benefits from the natural resource. Third, if a tourist industry develops based on recreational fisheries' guests we may have a commercial fisheries sector and a tourist sector competing for the same fish and fishing grounds.

10.2 SHORT-RUN ANALYSIS

In the short run we may neglect possible effects on the fish resource from anglers. However, in the long run such effects have to be included if the anglers' catch is of some importance compared with the size of the fish stock and its growth potential. Let us start with the simplest task – the short-run analysis of recreational fishing.

Assume that the demand for recreational fishing, measured by days of fishing, D, depends on:

- The price of the fishing permit (money per day of fishing, *$/D*)
- The quality of fishing, defined as the quantity of fish per day of fishing ($Q=kg/D$)
- The income and prices of alternative goods, assumed to be constant
- Recreational fishing being a normal good (demand increases with income)
- Utility maximization of a representative consumer
- A fish stock that is limited in size and potential yield – in other words, a scarce resource

We have a recreational fisheries sector with several resource firms and a competitive numeraire sector comprising the remaining economy. All in all there are *n* recreational fishermen (consumers), each with a utility function that is separable and linear in the numeraire good. Thus there are no income effects in the recreational fisheries and we can perform a partial equilibrium analysis. We shall analyse and compare competitive open access with a profit-maximizing resource owner. In some recreational fisheries the resource is limited to that of a lake or a river. This entity may be unique in the sense that recreational fishers' willingness to pay for fishing is different from for fishing in nearby lakes and rivers. In other cases a lake is a lake and a river is a river from the recreational anglers' point of view.

The parameters we are going to use are shown in Table 10.1.

Symbol	Definition	Unit (*)	Value (for Exercise 10.1)
	Exogenous:		
r	Maximum (intrinsic) growth rate	Year^{-1}	0.5
K	Carrying capacity	Kg	$4*10^3$
q	Catchability coefficient of the angler fishery	Kg/day^2	$4*10^{-5}$
α	Constant of the linear demand function	$/day	99.0
β	Slope of the linear demand function (the marginal willingness to pay for an angler day)	$/day^2	$3.125*10^{-3}$
γ	Quality constant of the linear demand function (the marginal willingness to pay for quality)	$/kg	6.25
c	Constant marginal cost of issuing permits	$/day	20.0
	Endogenous:		
X	The fish stock level	Kg	
H	Total catch per year (**)	Kg/year	
D	Total number of permits (angler days) per year	Days	
Q	Quality of fishing (catch per angler day)	Kg/day	
P	Price per angler day (price per permit)	$/day	
d	Number of permits per representative consumer	Days	
n	Number of anglers (consumers)	Number	

Table 10.1. Variables in the recreational fishery analysis
(*) One day means one angler day, which is one angler who fishes for one day.
(**) One year consists of a given number of days' angling.

In the previous chapters we have mainly worked with a constant price of fish to simplify the analysis, but without loosing track of the main bioeconomic issues. For the recreational fishery, however, we shall revert to the downward sloping demand curve, so well known from the micro economic theory. In general there are several possibilities for demand functions, including linear demand and constant elasticity demand. We shall stick to the former[29] and derive, from the consumer's utility-maximizing behaviour, the following linear inverse demand function:

$$p = p(D,Q) = \alpha - \beta D + \gamma Q \text{, for } Q > Q^0 \tag{10.1}$$

where Q^0 is the lowest fishing quality that attracts anglers to this particular fishery. The parameters α, β and γ are all positive. The inverse demand for recreational fishing is downward sloping in the number of fishing days and is positively affected by an increase in the quality of the fishing. Quality by definition depends on the catch rate, the catch per angler day. To simplify we now assume that quality equals the catch per angler day, which is $Q=H/D$. In this case γ expresses the marginal willingness to pay for catch per angler day and β expresses the marginal willingness to pay for an angler day.

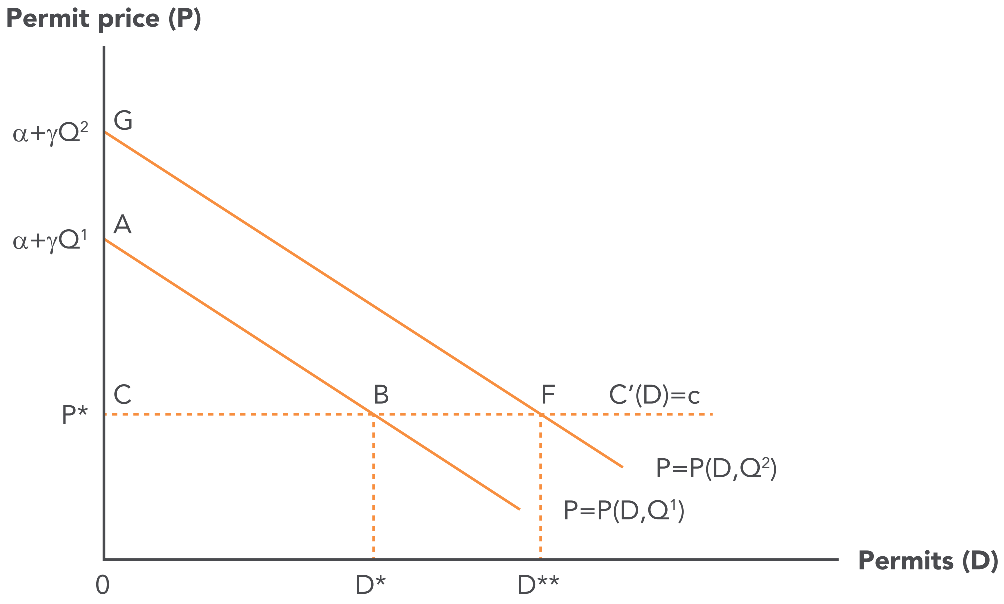


Figure 10.1. Demand and supply of angler days, short run

Figure 10.1 shows the downward sloping demand curves for two levels of quality, Q^1 and Q^2 with $Q^1<Q^2$. In this case the anglers' demand curves represent inverse demand for daily fishing permits for the given quality levels. With the quality of fishing equal to the catch per angler day, for the price p^*, the anglers want to purchase D^* permits if the quality equals Q^1, and D^{**} permits if the quality equals Q^2. For this price p^* the consumer surplus corresponds to the triangle CBA for the low quality and the triangle CFG for the high quality Q^2. There is no producer surplus in this case with the horizontal supply curve. Note that the demand curves in Figure 10.1 are for the short run when we neglect that the stock level is negatively affected by the recreational fishery.

The supply curve of angler permits reflects the aggregate marginal cost of issuing and handling permits and in Figure 10.1 this is drawn as a horizontal line at p^*. This means that the total cost of producing permits equals $C(D)=cD$, where c is the cost per permit. The marginal cost of permits is $C'(D)=c$. In other words the average and the marginal costs of issuing permits are the same. In a competitive market for fishing permits, as illustrated in this figure, the equilibrium price is limited from the cost side since $p=c$. We now easily derive the competitive number of angler days, $D^* = \dfrac{\alpha + \gamma Q - c}{\beta}$, for quality Q^1 and D^{**} for quality Q^2, where $D^*<D^{**}$. Thus the number of angler days at equilibrium increases with the quality of the recreational fishery and decreases with the cost of producing permits. The anglers' perception of quality is reflected in γ, implying that the competitive number of angler days increases with their marginal willingness to pay for quality. In this case with a linear demand curve there is a limit to how many days the anglers would like to go fishing, to be found where the demand curves intersect the horizontal axis, for $p=0$ in Figure 10.1.

In most countries recreational sea fishing is free of charge, but still the number of angler days is not infinitely large (see the case studies in Aas, 2008). To go fishing the angler will usually have to travel to the port, have suitable fishing gear and own or rent a boat – all costly activities. Thus the private costs of recreational fishing may set a limit to how many people actually go fishing, even if the fishery is free. However, as we have seen in the previous chapters, the harvest affects the fish stock to a greater or lesser extent, depending on the amount of effort targeting the resource. In the case of recreational fishing the total effort, equal to D above, equals the number of anglers times the average number of fishing days and it may well be that this significantly affects the resource. So far we have not included this important issue in the analysis. In some fisheries, for example in rivers and creeks, free access could easily cause heavy biological overfishing and also the extinction of fish stocks. We shall return to the resource issue below.

In the case of inland fisheries, in lakes and rivers, there usually exists some kind of private property where fishing rights are owned, or controlled, by landowners, farmers or local commons bodies (again, see Aas, 2008). In such cases the rights owner can achieve more than discussed above where the competitive solution did not generate any producer surplus, but only consumer surplus. Assuming that there is a unique source of fishing the willingness to pay is taken care of by a downward sloping demand curve as in Figure 10.1. For a given quality Q the total profit for the resource owner is

$$\pi(D,Q) = p(D,Q)D - c(D) = \alpha D - \beta D^2 + \gamma QD - cD\,. \tag{10.2}$$

Maximizing π with respect to D, treating the quality, Q, as given, implies that the resource owner should strive for a solution where the marginal revenue equals the marginal cost, as we know from the theory of the monopoly. With the profit function (10.2) this implies that

$$\alpha + \gamma Q - 2\beta D = c\,, \tag{10.3}$$

and the resource owner aims at $D^M = \frac{\alpha + \gamma Q - c}{2\beta}$ angler days by selling this number of licenses. Note that D^M is smaller than the competitive number of angler days, D^2, discussed above for quality Q^2. In fact with linear demand the resource owner should, to maximize his profit, aim at only half of the competitive number of angler days where anglers pay only the costs of supplying the permits. This is demonstrated in Figure 10.2. The consumer surplus is now reduced from the triangle CFN to the triangle LMN, whereas the producer surplus is increased from zero to the square CNML. This means that the social surplus is reduced by the triangle NFM.

As explained above the analysis related to Figure 10.1 and Figure 10.2 excludes any effect the anglers' fishing might have on the resources. Is this a realistic analysis? Well, in some cases it may be sufficient not to include the resource in discussing recreational fisheries management. For example, if anglers just exploit the fringes of a big fish resource, which is mainly utilized by commercial fishermen, and they do this in one or a few scenic localities, their demand is really for the joint amenities and fish resource. If each locality has something unique to offer anglers, who differ in preferences, there may be a separate demand curve for each of them. In such cases the proper quality of the recreational fishery is determined by the commercial fishery, through its fishing pressure and effect on the stock. However, local communities or landowners may exert some market power and make money from the anglers' willingness to pay for the joint product of fishing and terrestrial amenity.

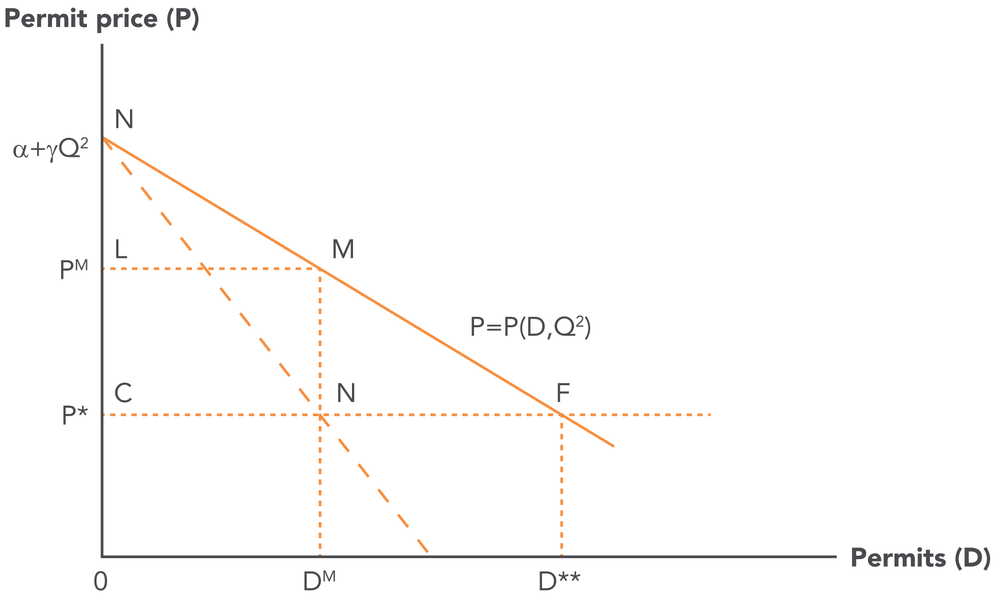


Figure 10.2. The sole owner's adaptation

10.3 LONG-RUN ANALYSIS

How can we include in a simple way the stock and the fishing pressure in the analysis of recreational fisheries, knowing that in some actual fisheries this is an issue of interest? The demand curves in Figures 10.1 and 10.2 are downward sloping in angler days, D, for a given quality of the fishery, measured by Q. The more angler days, the more the stock will be negatively affected and the quality of the fishing reduced via the average catch per angler day, Q. Thus in the long run the demand curve will shift inward, instead of staying constant as we assumed for the short-run analysis in the two figures discussed above. This is demonstrated in Figure 10.3 where the uppermost curve corresponds to the demand curve for the constant Q^2 and the lowermost curve is the resource adjusted demand curve that we have to consider in a long-run analysis. The latter reflects that for each level of angler days there exists a long-run equilibrium level for the fish stock and this stock level determines the catch per angler day, the recreational fishery quality Q. How much the long-run demand curve differs from the short-run curve depends on the biological productivity and on the anglers' efficiency and willingness to pay for quality. Let us have a closer look at this by including an explicit growth model in the analysis. To make it simple we shall use a familiar growth model, the logistic growth used extensively in Chapter 5 in the Gordon–Schaefer model.[30]

The growth function is $\dot{X} = rX(1-\frac{X}{K})$, with X as the fish stock level, r is the intrinsic growth rate and K is the carrying capacity for the stock. The angler harvest function is $H=qDX$, where q is the catchability constant and, recalling the analysis of the Gordon–Schaefer model in Chapter 5, we have (see equations 5.2–5.7) that the long-run productivity will vary with the number of angler days in this way:

$$Q = Q(D) = \frac{H}{D} = qK(1 - \frac{qD}{r}), \tag{10.4}$$

assuming that angling is the only type of fishing occurring.[31] The angler harvest function in (10.4) corresponds to the long-run harvest function *H(E)* used extensively previously, including in Chapters 3 and 5. Substituting for *Q* from (10.4) into (10.1) gives

$$P(D) = \alpha - \beta D + \gamma qK(1 - \frac{q}{r}D) = a - bD, \tag{10.5}$$

where $a = \alpha + \gamma qK$ and $b = \beta + \frac{\gamma qK}{r/q}$. Thus the resource adjusted angler demand curve, in (10.5), shown in Figure 10.3, is steeper than the short-run demand curve in (10.1), since $b > \beta$, but also this curve is linear in the angler days, *D*. The resource adjusted demand curve is corrected for the resource effect of angling, which is the negative effect angling has on the stock and on the catch per angler day. These effects can not be neglected in the "long" run.

The student should now complete exercise 10.1.

In Figure 10.3 the short-run demand curve has the negative slope β and the resource adjusted demand curve has the steeper negative slope *b*. The difference between the two slopes increases with the anglers' willingness to pay for fishing quality (measured by γ) and with the angling productivity, which equals the catchability constant *q*. The biological characteristics of the stock, represented by *r* and *K*, also affect the resource adjusted demand curve, as seen from equation (10.5). The willingness to pay for an angling day, *P(D)*, is higher the more productive the resource is, measured by *r* and *K*.

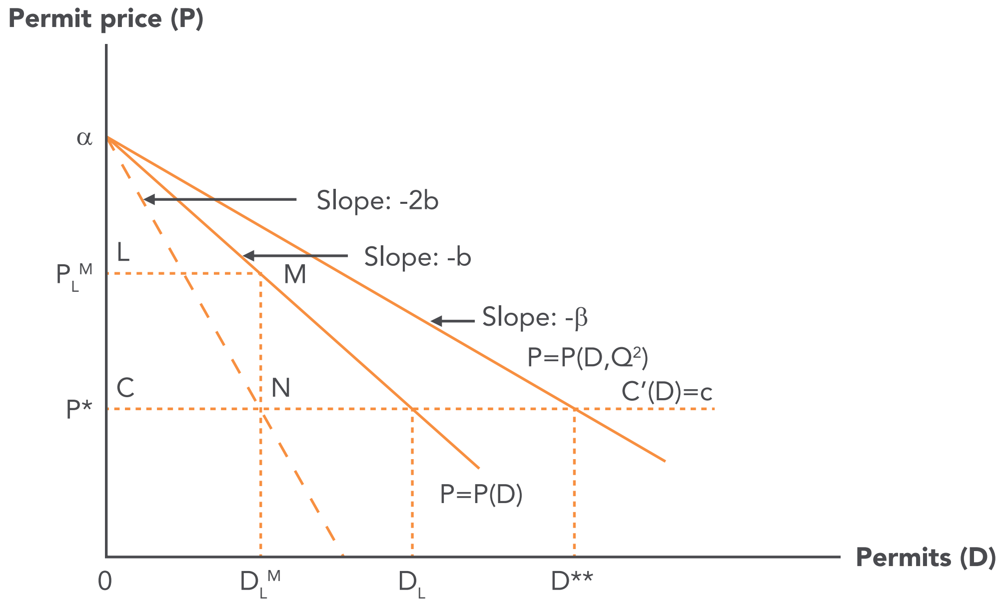


Figure 10.3. The resource adjusted angler demand curve and the short-run demand curve. The latter is shown for $Q=qK$ implying that in this special case the intersection point on the vertical axis is the same for all three curves.

What we called the competitive solution in Figure 10.2, for D^{**} with permit price P^* is not a sustainable solution. It is not a bioeconomic equilibrium since the limits of the fish stock production are excluded from the analysis. Thus the resource adjusted demand curve implies that D_L in Figure 10.3 is the maximum number of permits that could be issued at the price P^*. For D_L there will be equilibrium in both the market for permits and in the sea for the stock. We may call this the competitive angling equilibrium.

If the owner of the angling resource maximizes the net value of the fishery, the number of angling permits should be reduced to D_L^M in Figure 10.3, based on the same reasoning as we used in Figure 10.2. With D_L^M permits the market price will be P_L^M, which is considerably higher than P*. Note that the surplus of the resource owner, equal to the square CNML in Figure 10.3, is smaller than the corresponding surplus in Figure 10.2. The important difference between the two is that only that of Figure 10.3 is sustainable. From this we conclude that if the anglers of a recreational fishery affect the resource this effect must be taken into account when considering the number of permits that should be issued.

We commenced this chapter by defining recreational fishing as fishing for fun, and continued by including days of fishing and quality as two major variables in the analysis. As the indicator for quality we chose catch per day of fishing and demonstrated that this is affected by the activities of the anglers. This way the recreational fishery can be analysed within the framework of bioeconomic modelling, now well known from the previous chapters. Our analysis includes the basics that distinguish recreational fisheries from commercial fisheries. However, recreational fisheries around the world vary in the type of natural resources, property and user rights and the way these fisheries are governed (many examples are given in Aas, 2008). Compared with our model above, one type of difference has to do with the biology of the targeted fish stock. For example, in salmon fisheries in the North Atlantic the majority of fish die after spawning and the stock growth function is skewed to the left with the maximum sustainable yield at a lower stock level than half of the carrying capacity (see Olaussen and Skonhoft, 2008). Another type of difference has to do with the utility function of the anglers. Some consumers may prefer tranquillity, with their utility being negatively affected by the number of anglers and angler days. If their willingness to pay for this is sufficiently high some resource owners, for example of salmon rivers, may find it profitable to market their services to the high-paying few rather than to the mass market. This seems in particular to be the case if the average size of the fish matters and not just the weight of the catch – the angling market value of fishing a ten kg salmon may be much higher than the aggregated value of ten salmon or trout of one kg each. In a survey of Norwegian rivers, 92 per cent of sport fishermen reported that the quality of the river in terms of the average catch per day was important. In addition, 72 per cent reported that the price of fishing permits was important (Fiske and Aas, 2001, quoted from Olaussen and Skonhoft, 2008). The issues mentioned here, and several others, have been discussed in the literature (see e.g. McConnell and Sutinen, 1979; Bishop and Samples, 1980; Anderson, 1983 and 1993; Rudd et al., 2002; not to forget two major books, Pitcher and Hollingworth, 2002 and Aas, 2008).

There is a great variation around the world in institutional arrangements regarding property rights and governance for the resources in recreational fisheries. This is partly reflected in the many ways recreational fisheries are managed. We have analysed the case of trade in fishing permits per angler day. Related measures could be to combine this with other measures, such as free or inexpensive access for members of a local commons and auction to the highest bidder of some fishing days, if the river or lake is owned in common by a community. Output control could also be used, for example a bag limit on the size of catch per angler per day. In addition to the permit price anglers might have to pay a fee per fish or per kg of fish. A more controversial way of limiting the catch is to use the catch and release method. If for example the stock consists of few big spawners that are necessary for the long-run sustainability of the fishery the anglers might have to release such fish into the water immediately after catching them. This may be controversial mainly for two reasons: first, uncertainty about the survival rate of the released fish; second, some people do not like the idea of having fish nearly killed just for the pleasure of man, even though hunting and fishing have for thousands of years given pleasure, food and money to people. Recreational fisheries management remains to be just as rich and complex, if not more, in theory and actual cases to give pleasure and challenges to generations to come of students and researchers.

Exercise 10.1

The demand for angler days in a recreational fishery can be described with the linear inverse demand function in equation (10.1). This recreational fishery is regulated by the use of angler day permits. In the short run the harvest depends on the number of angler days and the stock level, and we assume this is according to the Schaefer harvest function $H=qDX$, with the definition of symbols given above in this chapter. The growth of the stock follows the logistic growth law (see Chapter 5) and the long run equilibrium harvest equals the growth, $H(X) = rX(1-\frac{X}{K})$. By use of the variables and values in Table 10.1, answer the following questions:

1. Draw a figure of the short-run demand curves for Q_1=0.06 and Q_2=0.15 (see equation (10.1).
2. Derive the long-run average catch per angler day, which is an indicator Q of the quality of the fishery (tip: see Chapter 5, equations (5.2)–(5.7), in particular the catch per unit of effort equation).

3. Derive the long-run demand function (price as a function of angler days), first by use of symbols, then plot this demand curve into your figure with the two short-run demand curves.
4. Give a verbal explanation of why there is a difference in the slope of the short-run and long-run demand curves for angler day permits.
5. Prove and explain why the long-run and short-run demand curves intersect the P axis at the same point for $Q=qK$.
6. What is the competitive(long-run equilibrium) number of permits if the constant marginal cost of issuing permits is $c=10.0$ \$/permit?
7. What is the maximum value of the quality indicator, $Q=Q_{max}$?

PART III AQUACULTURE[32]

11 AQUACULTURE PRODUCTION

11.1 INTRODUCTION

Aquaculture includes several modes of production and many different species, both animals and plants, from the sea, brackish and fresh water. In developing countries, inland culture in earthen ponds is by far the largest way of producing finfish. However, use of floating cages is also increasing in these countries. Most of the fish production is for human consumption, but often by-products are used for animal feed, directly or through reduction into fishmeal and oil. In terms of food supply, aquaculture provided more fish than capture fisheries for the first time in 2014. By 2014, more than 580 species and/or species groups were farmed in about 200 countries and geographical entities.

According to the United Nation's Food and Agriculture Organisation (FAO, 2016), the global production of aquatic animals from aquaculture amounted to 73.8 million tonnes in 2014, at an average price of 2.17 USD/kg (FAO, 2016). Of this, finfish and crustaceans amounted to 49.8 and 6.9 million tonnes, at an average price of 1.99 and 5.25 USD/kg, respectively. With 45.5 million tonnes – or more than 60 per cent of the global fish production – in 2014, China is at the very top among aquaculture producing countries. Other major aquatic animal producers are India, Vietnam, Indonesia, Bangladesh and Norway. In addition, 27.3 million tonnes of aquatic plants were cultured at an average price of 0.21 USD/kg, thus a low value production compared to fish. At the higher end of valuable aquatic animals are salmon (including trout) and shrimp (including prawn), the number one and two fish species (though shrimp is not a fish) in world trade by value. The majority of these products globally are aqua cultured.

Aquatic animals include finfish from inland and the marine, molluscs and crustaceans. Figure 11.1 shows that the quantity in capture fisheries stagnated in the 1990s and that aquaculture continued to grow, outpacing capture in 2014. Aquatic plants are a significant part of aquaculture production that takes place mainly in Asia, including Japan. In Figure 11.1, capture includes some aquatic plants: comparing this with Figure 1.1, which excludes aquatic plants, we notice a relatively small difference. Thus, on a global scale, capture of aquatic plants is small compared to that of aquaculture plants.

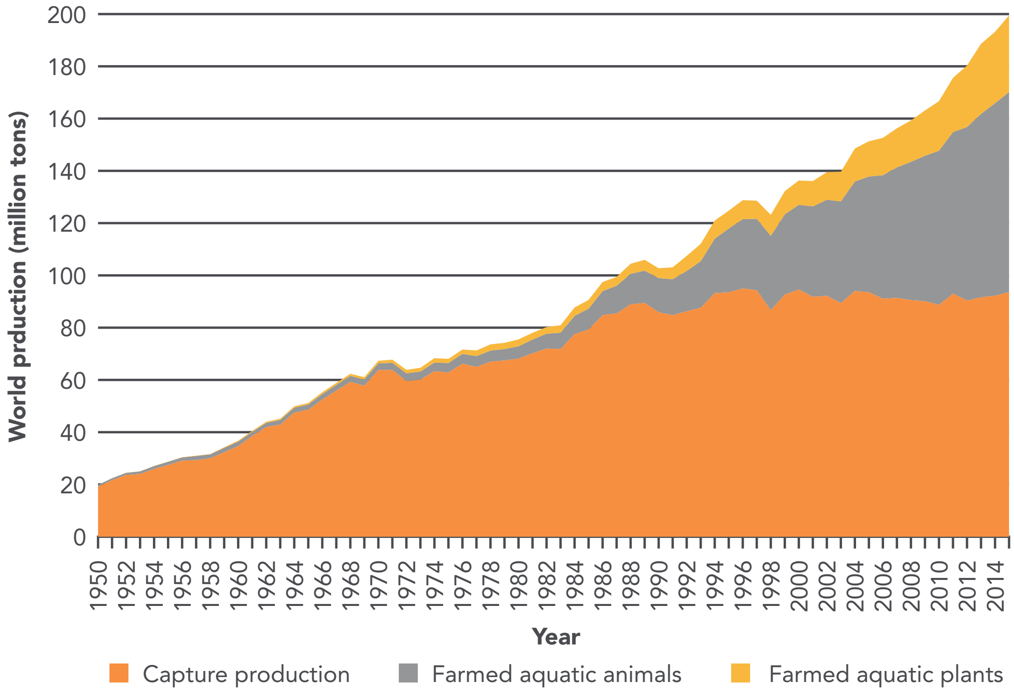


Figure 11.1. World capture fisheries and aquaculture production of animals and aquatic plants. Capture includes some aquatic plants. 1950–2015.
Sources: FAO, 2016; FAO, 2017a; Nadarajah. S., UiT, The Arctic University of Tromsø, personal communication.

To understand aquaculture development, it is important to distinguish between fed and non-fed species. For the former, the feed cost is usually the largest component of the total production cost (Table 11.2). In addition, there has been ongoing debate as to whether the limited supply of fishmeal and oil may hamper the future growth of aquaculture (Olsen and Hasan, 2012). Fishmeal is an important feed ingredient not only for carnivorous fish, but also for herbivorous/omnivorous species, causing demand to grow. On the other hand, the global supply of raw materials for fishmeal and oil from capture fisheries is limited.

Aquaculture production requires at least these specific inputs: water, a place for enclosures at sea or inland to keep fish, and technology and knowledge, in addition to what all businesses need, such as capital, labour, energy, other inputs and markets. Feed is an important input in most aquaculture, though some fish and other aquatic animals find their food in the natural environment. In the latter case, the difference from capture fisheries is that the fish are the property of someone and are grown in enclosures, whether earthen ponds, rice fields or net-fenced river stretches.

Aquatic plants include seaweeds and microalgae. Interestingly, by volume, half of the world's aquaculture production in 2014 was realised without feeding. Of this, plants comprised a larger element than filter-feeding animals. The latter includes the oily freshwater fish bighead carp and silver carp, belonging to the largest species group of the world's farmed fish (Box 11.1). Despite the high share in terms of quantity, the value share of plants was less than five per cent of aquaculture in 2014. Seaweed is consumed by coastal dwellers in many places in the world, but particularly in East Asia. It is cultivated and harvested for the extraction of alginate substances used in foods such as confectionery, meat and poultry products, desserts and beverages, as well as in fertilizer, toothpaste, cosmetics and paints. A range of microalgae species are produced in hatcheries and are used in a variety of ways for commercial purposes. The biodiversity of microalgae is enormous, and they still represent a largely untapped resource. It is estimated that there are hundreds of thousands of species, of which about 50,000 are described. Over 15,000 novel compounds originating from algal biomass have been chemically determined. Most of these microalgae species produce unique products for food, drinks and industrial products, for both local and international markets. Fish oil is famous for its omega-3 fatty acids, but fish do not actually produce omega-3, instead accumulating their omega-3 reserves by consuming microalgae. These omega-3 fatty acids can be obtained in the human diet directly from the microalgae that produce them.

> "Culture-based fisheries (CBF) is a practice to enhance fish stocks in waters that do not have enough natural recruitment to sustain a fishery. CBF practices are usually applied in small water bodies such as village dams and irrigation reservoirs. Fish growth is driven by the natural productivity of the waters. Usually there is no feeding and the fish are left to forage on natural food supplies. Ownership and management

of the stock distinguish CBF as form of extensive aquaculture. CBF practices can help farmers to improve their food production and income by harnessing the natural productivity of rural ecosystems" (NACA, 2018).

Box 11.1 Carp

Carp comprises various species of oily freshwater fish, belonging to a very large family of fish native especially to Europe and Asia, and is the most farmed fish globally. Carp (cyprinids) contribute over 30 million metric tonnes to fish production worldwide and account for approximately 40 per cent of total global aquaculture finfish production and 45 per cent of total freshwater production. (For a comprehensive review of carp biology and ecology, see Pietsch and Hirsch, 2015.) Carp can grow very big, up to 1.5 m long and weighing 40–50 kg, though with variation among the many carp species. For commercial use, carp includes some of the species with big individuals. In many countries, carp is considered a good and healthy food and achieves higher prices than tilapia, which is a much leaner fish. Some species of carp can move into brackish water but return to fresh water to spawn. In the USA, some species of carp in the wild are considered invasive species and there, as well as in some other countries, large sums of money are spent on carp control.

Various species of carp have been domesticated and raised in captivity. This has been known for more than two thousand years in China, where carp are mainly raised in ponds and are well recognised in the markets. In Western Europe, as more fish species have become available for consumers, the importance of cultured carp has diminished. Other oily fish, in particular salmon and trout, has increased in supply at a decreasing price through intensive farming and increased demand. However, in Central and Eastern Europe, including Russia, carp production in ponds is still the major form of aquaculture.

Selective breeding programmes for the carp include improvement in growth, shape and resistance to disease, as well as adaptation to environmental conditions such as variations in temperature and tolerance of cold and warm water. The major carp species traditionally used in Chinese aquaculture include black, grass, silver and bighead carp. Towards the end of the last century, scientists developed what is known as Jian carp, which has a higher growth rate and a better feed conversion rate than the natural carp species. Over half the total aquaculture production of carp in China has now converted to Jian carp.

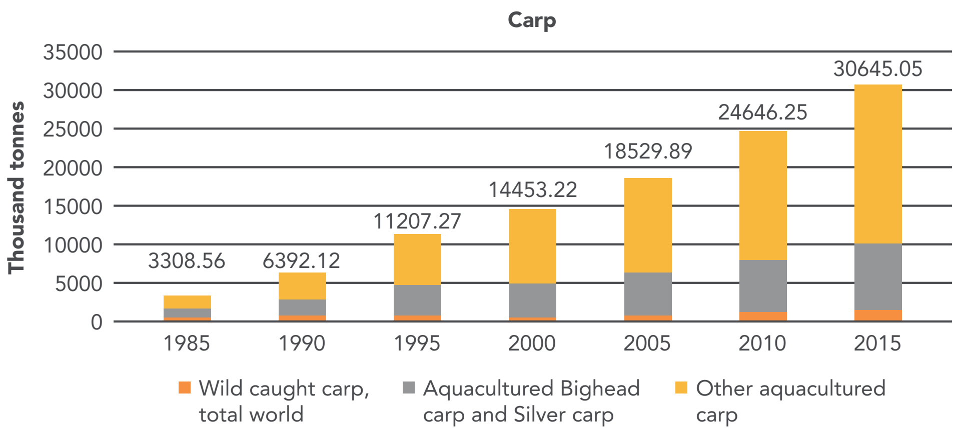


Figure 11.2. Annual production of carp, including barbels and other cyprinids, in thousand tonnes. Box and figure sources: FAO (2016); FAO (2017a); Wikipedia (2017); Thuy Thanh, P.T. and Nadarajah. S., both UiT, The Arctic University of Norway, personal communications.

Aquaculture carp are totally dominating the global production of such species, as shown in Figure 11.2. Bighead carp and silver carp are the major non-fed aquaculture species in the world. The production of these two species increased by a factor of seven from 1985 to 2015, whereas the other aquaculture carps increased by a factor above 13, and in 2015 reached more than 20 million tonnes. In comparison, wild caught carp increased by a factor of less than three, exceeding 1.5 million tonnes that year.

11.2 THE GLOBAL PICTURE

We have seen in Figure 11.1 that for several decades there has been a strong growth in aquaculture production. This is also the case for the product value at the farm gates. Figure 11.3 shows the annual percentage growth rates in terms of both quantity and value from 1984 to 2015, as well as the global total quantity for this period (right hand side). The value growth fluctuates more than the quantitative growth. This may be due to price and currency volatilities, in particular the latter since all prices in national currencies have been recalculated in USD.

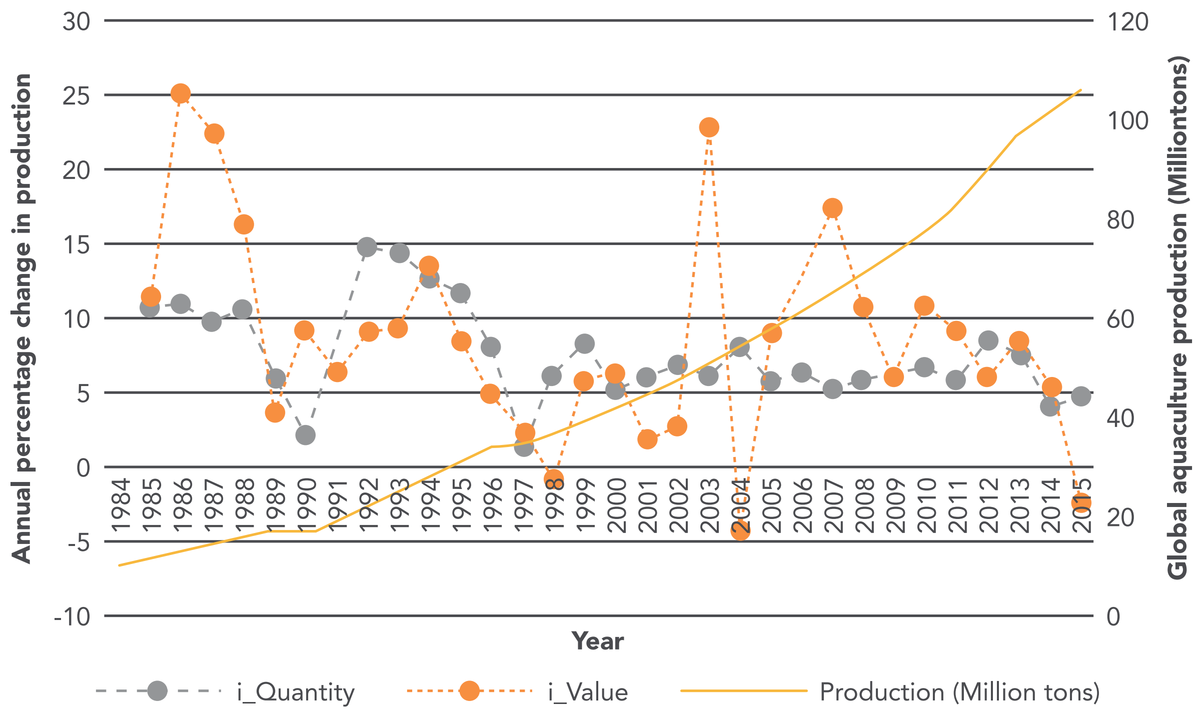


Figure 11.3. Global aquaculture production and average annual change in quantity and value (1984–2015). Sources: FAO (2016); FAO (2017a); Nadarajah and Flaaten (2017); Nadarajah. S., UiT, The Arctic University of Norway, personal communication.

The average annual changes are 7.6 per cent and 8.7 per cent for quantity and value, respectively, over the period 1984–2015. The higher average value growth compared to quantity growth is probably due to the increase in global demand from a larger world population with increased average income. China is in a division of its own both with respect to quantity and value following tremendous growth over the last three decades. The compounded annual growth of China from 1984 to 2015 was 8.9 and 10.4 per cent of quantity and value, respectively. The production in 2014–2015 in terms of quantity and value, and annual growth rates for more than 70 aquaculture producing countries in the years 1985–2015 are shown in the Annex (Table A11.1). This is based on methods described in Nadarajah and Flaaten (2017). This table also demonstrates that several other major aquaculture countries, including Indonesia, Chile, Vietnam, Norway, Egypt and Myanmar, had even higher growth rates than China. This is also the case for some smaller aquaculture countries, such as Tunisia, Sri Lanka, Nicaragua, Iceland and Ghana. However, the total quantity of production in these five countries in 2015 was only 0.2 per cent that of China.

11.3 THE LEAD PRODUCERS

The biennial FAO report on the state of the world's fisheries and aquaculture contains many facts about aquaculture production, markets and development, as well as discussion on selected issues. Table 11.1 summarises some important figures for the top 25 producing countries and entities, sorted by value in 2014 (FAO, 2016). China is at the top for most groups of animals and plants, as well as for total quantity and value, and has a very diverse production of both animals and aquatic plants. Other Asian countries are also at the top of the world's producers. Inland production of finfish is dominated by four Asian countries, namely India, Indonesia, Vietnam and Bangladesh, and the north African Egypt. Marine finfish are more widely spread geographically, with Norway, Chile and Indonesia in the lead. Mollusc production is also widespread, including in Japan, Korea, Chile, Spain, the USA, Vietnam and France. Crustaceans – mainly high value shrimp – are produced mainly in Asia (India, Indonesia, Vietnam and Thailand) but also in Ecuador in South America. In addition to China, Indonesia, the Philippines and South-Korea are the major producers of aquatic plants, which in general fetch lower prices than aquaculture animals. Finally, the six leading countries together have almost 70 per cent of the total world production in value terms.

	Major Producers	Finfish		Molluscs	Crustaceans	Other aquatic animals	Total aquatic animals	Aquatic plants	Total aquaculture production (quantity)	Total aquaculture production (value)
		Inland aquaculture	Marine/ Coastal aquaculture							
		Thousand tonnes								Million USD
1	China	26 029.70	1 189.70	13 418.70	3 993.50	839.50	45 469.00	13 326.30	58 795.30	75 603.50
2	India	4 391.10	90.00	14.20	385.70	…	4 881.00	3.00	4 884.00	10 768.50
3	Indonesia	2 857.60	782.30	44.40	613.90	0.10	4 253.90	10 077.00	14 330.90	10 567.90
4	Chile	68.70	899.40	246.40	…	…	1 214.50	12.80	1 227.40	10 309.20
5	VietNam	2 478.50	208.50	198.90	506.20	4.90	3 397.10	14.30	3 411.40	7 903.70
6	Norway	0.10	1 330.40	2.00	…	…	1 332.50	…	1 332.50	7 059.60
7	Bangladesh	1 733.10	93.70	…	130.20	…	1 956.90	…	1 956.90	4 853.30
8	Japan	33.80	238.70	376.80	1.60	6.10	657.00	363.40	1 020.40	4 745.60
9	Thailand	401.00	19.60	209.60	300.40	4.10	934.80	…	934.80	2 556.50
10	Republic of Korea	17.20	83.40	359.30	4.50	15.90	480.40	1 087.00	1 567.40	2 156.60
11	Philippines	299.30	373.00	41.10	74.60	…	788.00	1 549.60	2 337.60	2 135.90
12	Egypt	1 129.90	…	…	7.20	…	1 137.10	…	1 137.10	2 024.80
13	Ecuador	28.20	-	…	340.00	…	368.20	…	368.20	1 961.20
14	Myanmar	901.90	1.80	…	42.80	15.60	962.20	2.10	964.30	1 867.60
15	Brazil	474.30	…	22.10	65.10	0.30	561.80	0.70	562.50	1 535.50
16	Taiwan Province of China	117.30	97.80	99.00	21.90	3.60	339.60	1.00	340.60	1 378.50
17	United Kingdom	13.50	167.30	23.80	…	…	204.60	…	204.60	1 318.20
18	United States of America	178.30	21.20	160.50	65.90	…	425.90	…	425.90	1 108.10
19	Malaysia	106.30	64.30	42.60	61.90	0.60	275.70	245.30	521.00	1 023.70
20	Turkey	108.20	126.10	…	…	0.10	234.30	…	234.30	970.80
21	France	43.50	6.00	154.50	-	…	204.00	0.30	204.30	967.80
22	Iran (Islamic Republic of)	297.50	0.10	…	22.50	…	320.20	…	320.20	967.00
23	Nigeria	313.20	…	…	…	…	313.20	…	313.20	894.50
24	Spain	15.50	44.00	222.50	0.20	-	282.20	-	282.20	562.60
25	Korea, Dem Peop Republic	3.80	0.10	60.20	…	0.10	64.20	444.30	508.50	125.60
	Top 25 Subtotal	42 041.50	5 837.40	15 696.60	6 638.10	890.90	71 058.30	27 127.10	98 185.50	155 366.20
	World	43 559.30	6 302.60	16 113.20	6 915.10	893.60	73 783.70	27 307.00	101 090.70	166 909.60
	Percent of top 25 in world total	96.50	92.60	97.40	96.00	99.70	96.30	99.30	97.10	93.08

Table 11.1 Top 25 producers (quantity), sorted by production value, and main groups of farmed species, 2014. Sources: FAO, 2016; FAO, 2017a; Nadarajah. S., UiT – The Arctic University of Tromsø, personal communication.

Notes: … = production data not available or production negligible. Rounding causes minor discrepancies and in a few cases, sub totals do not equal the sum of main groups (in particular for Indonesia).

Box 11.2 Tilapia

Tilapia is the common name for nearly a hundred species of cichlid fish. Tilapia are mainly freshwater fish and more rarely found in brackish water. Historically, they have been of major importance in artisanal fishing in Africa, in mythical old Egypt and in Biblical times. Tilapia are of increasing importance in aquaculture, and for consumers are popular due to their low price, easy preparation and mild taste.

Tilapia physiology is such that they are efficient feeders that can capture and process a wide variety of food items. Unlike carnivorous fish, tilapia can feed on algae or any plant-based food. This reduces the cost of tilapia farming and makes tilapia the preferred 'aquatic chicken' of the trade. Nile tilapia (*Oreochromis niloticus)* can grow as long as two feet. Tilapia require warm water: most species will die at a range of 11° to 17° C. They have spread widely in fresh and brackish tropical and subtropical habitats, disrupting native species significantly. Because of this, they are on the IUCN's list of the world's one hundred worst alien invasive species. The fast-growing tilapia of North Africa are tolerant of stocking density, are adaptable and have been introduced to (and are farmed extensively in) many parts of Asia and elsewhere.

In modern aquaculture, wild-type Nile tilapia are not that popular due to their dark flesh, whereas 'red' breeds with lighter meat have been developed and are more popular. Tilapia are a good source of protein and are popular among artisanal and commercial fisheries, but are low in the healthy omega-3 fatty acids.

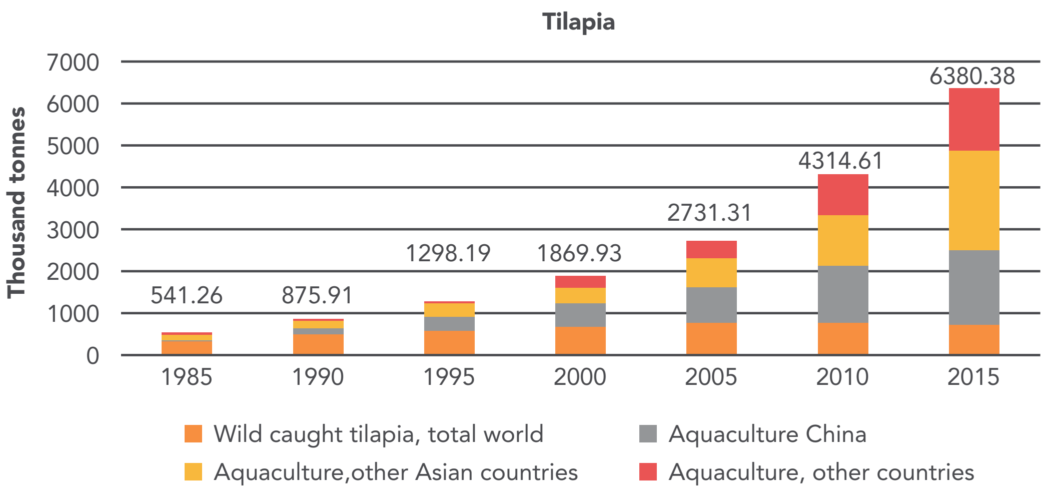


Figure 11.4. Annual production of tilapia, including other cichlids, in thousand tonnes.
Box and figure sources: FAO (2016); Wang and Lu (2016); Wikipedia (2017); Thuy Thanh, P.T. and Nadarajah. S., both UiT, The Arctic University of Norway, personal communications.

In 1985, the total global production of tilapia was more than half a million tonnes and 60 per cent of this was wild caught (Figure 11.4). Wild caught tilapia reached its historic maximum in 2011 with about 780 thousand tonnes. In 2015, the total global production had arisen to almost 6.4 million tonnes, of which wild caught comprised only 11 per cent. Figure 11.4 shows that the Asian countries are the major producers of tilapia, China being the most prolific. Note, however, that other countries had the relatively largest increase in aquaculture production, from hardly anything in 1985 to above 1.5 million tonnes in 2015. For a review of tilapia production and potential in Africa, see Cai et al. (2017).

11.4 TWO SUCCESSFUL COUNTRIES

Let us have a closer look at three successful aquaculture industries in two very different natural environments: fish and shrimp in tropical Vietnam and salmon (*Salmo salar*) in partly arctic Norway. In the former case, water temperature is often as high as 30° C, whereas for the latter, the winter temperature in the north can go down to just a few degrees Celsius. The upper part of Table 11.2 gives in percentages some major cost shares, while the lower part gives some key figures in national and US currency. Fish from these three industries are exported to highly competitive markets all over the world. Shrimp and salmon both fetch high market prices, whereas the white fish pangasius (*Pangasius hypophthalmus* and *Pangasius bocourti*) has a low price, less than one fifth of the other two at the farm gate. White leg shrimp (*Litopenaeus vannamei*) (WLS) now account for more than half of the total shrimp production in Vietnam, despite the lower price than tiger shrimp (*Penaeus monodon*), ranked second. The main reason for this is that the production cycle of WLS is 3–4 months, against six months for tiger shrimp.

Cost item	Pangasius, Vietnam[3], 2016	White leg shrimp Vietnam[3], 2014	Salmon Norway, 2016
	Cost shares %	Cost shares %	Cost shares %
Smolt/seed	10.4	11.88	9.39
Feed	81.84	41.17	42.97
Labour[1]	1.08	4.91	6.73
Insurance			0.38
Pond rental	1.05		
Power		11.68	
Other operating cost	3.47[4]	13.06[5]	25.72[2]
Depreciation	0.45	17.30[6]	5.32
Net financial cost	1.16	-[7]	-0.12
Operating cost, all	99.44	100	90.4
Slaughter	0.56	-[8]	9.63
Total cost	100	100	100
Total cost, national currency	21 440.00	108 832.40	33.86
Revenue, national currency	22 600.00	120 336.06	50.59
Profit	1 160.00	11503.66	16.73
Exchange rate, per USD	22 368.25	21 193.08	8.4
Total cost, USD	0.96	5.14	4.03
Revenue, USD	1.01	5.68	6.02
Profit margin	5.1	9.5	33.1

Table 11.2 Cost structure of three aquaculture industries. Cost and revenue per kg fish at farm gate
Sources: Salmon – Directorate of fisheries, Norway (2017)
Pangasius – Duy Nguyen Ngoc, PhD, Lecturer, Nha Trang University, personal communication, (duynn.ntu@gmail.com); Thanh Thuy Pham, PhD, Post Doc, UiT – The Arctic University of Norway, personal communication, thanh.thuy@uit.no
Shrimp – Long et al. (2017); Thanh Thuy Pham, PhD, Post Doc, UiT – The Arctic University of Norway, personal communication.

Table notes:

1. May include some management cost
2. Includes repair, maintenance, administration, fish health, energy, and environmental measures
3. Dong Thap province and South Central Vietnam for pangasius and shrimp, respectively
4. Includes Chemicals/pharmacy, power, pond regeneration and materials
5. Pond regeneration is partly included in Labour
6. Includes maintenance and other fixed cost
7. Net financial cost is very small. Some may have been included in Other
8. The buyer usually harvest the shrimp and carry the cost (some cost to the farmer could be included in Labour)

In Vietnam, pangasius is produced mainly in earthen ponds and shrimp (Box 11.3) in shallow ponds on or near riverbanks. The pangasius industry, like the shrimp and salmon industries, is very dependent on the export market, since the domestic market for this fish is very small. Salmon in Norway, and in other Atlantic countries, are produced mainly in floating cages in coastal areas, but first as juveniles in freshwater tanks on land to reach the smolt (recruits) stage before going into the sea. Table 11.2 shows more similarities in the cost structure between salmon in Norway and white leg shrimp in Vietnam than between shrimp and pangasius in Vietnam. Salmon and shrimp feed have about the same cost share (about 42–43 per cent), whereas pangasius, a much cheaper fish, has a very high feed cost share of more than 80 per cent. Pangasius is also less labour intensive than the other two. However, the recruitment cost is about the same in the three groups, measured as the percentage of total cost per kg fish produced – about ten per cent.[33]

Pangasius export from Vietnam increased from almost nothing in 2000 to nearly 1.2 million tonnes in 2016, at a value of 1.7 billion USD, while the Norwegian aquaculture salmon export grew from practically nil in the 1970s to almost 1.0 million tonnes (product weight) in 2016, at a value of 7.3 billion USD. That year, the total production (live weight) of salmon in Norway amounted to 1.3 million tonnes, with a farm gate value of 7.6 billion USD.

In 2015, Vietnam had a much higher aquaculture production in terms of quantity than Norway, but only a slightly higher value (Table 11.1). Both countries have long, suitable coasts and showed record high growth rates in aquaculture over the three decades 1985–2015, with double digits annual growth in both quantity and value (Annex Table A11.1). Noting that Vietnam is a one-party socialist republic headed by the Communist party and Norway is a democratic, market economy kingdom, how was this possible when the overall institutional systems differ so immensely? The story of why growth rates differ between countries has been discussed thoroughly in the literature, both in macro- and micro-economics (Hall and Jones, 1999) and in natural resource economics (Ploeg, 2011; Nadarajah and Flaaten, 2017), but is considered outside the scope of this book. Let us just mention that after the end of the American war in 1975 and the unification of North and South Vietnam, the Communist government largely expropriated private property and collectivised the industries. After two decades of low, and even negative, economic growth and a disastrous food situation for people, a new economic policy was gradually put in place from the mid-1980s. This institutional change towards a market economy and the long and suitable coast are two major pillars of the growth in aquaculture that followed. Also, aquaculture growth in Norway was boosted by institutional change, from legal entities of small-scale family operators to legal encouragement of mergers and acquisitions, but with restrictions on entry with the aim of limiting negative environmental effects. The differences and similarities between Vietnam and Norway illustrate that aquaculture growth can be achieved in countries with different institutional and natural conditions (Table 11.2; Annex Table A11.1; Nadarajah and Flaaten, 2017).

Aquaculture shrimp in Vietnam

Shrimp are cultured in over 60 countries today. Modern shrimp farming started in the early 1970s and became significant in the early 1990s. It provides employment, directly and indirectly, for millions of people globally. The system for shrimp production has developed technologically and economically over time. In the case of Vietnam, it started with a mainly integrated shrimp-mangrove system with no feeding, no chemicals, wild seeds and, often, joint production of tiger shrimp (*Penaeus monodon*) and mud crab. This system is still (2017) in use and the area of productivity was about 350–400 kg/ha/year for shrimp (tiger shrimp 50–60 per cent of this), 50–100 kg/ha/year for mud crab and 100–150 kg/ha/year for fish (Seafood Trade, 2018; Shrimp News, 2018). Gradually, improved extensive farming with casual feeding and tidal water exchange surpassed the use of the traditional integrated shrimp-mangrove system. Productivity increased somewhat for both shrimp and crab. Rotational rice-shrimp farming was introduced mainly after 2001, with shrimp culture in the dry season and rice in the rainy season. Water was mainly pumped, with limited exchange, and the feed was in pellet form. Furthermore, over the following decade, semi-intensive and intensive production (these are classified according to pond size, water use, capital, labour, feed and chemicals used, and stocking densities) more than doubled the shrimp productivity.

Before 2000, all shrimp cultured in Vietnam were black tiger; since 2002, many shrimp farmers have changed to white leg shrimp *(Litopenaeus vannamei*) that has faster growth and allows one extra production cycle per year – three as compared to two. With intensive farming, production gradually shifted from monodon to vanamei, with a further productivity increase. Annual yield increased to 2.3 tonnes/ha and 2.5 tonnes/ha for monodon in 2006 and 2013, respectively. For vanamei, the corresponding numbers are 3.1 tonnes/ha and 3.8 tonnes/ha. The brood stocks for seed production differ, with wild caught for monodon and imported or domesticated for vanamei.

In 2016, total brackish water shrimp production in Vietnam was estimated at 609.3 thousand tonnes, of which black tiger shrimp amounted to 251.7 thousand tonnes and white leg shrimp 357.6 thousand tonnes. The total shrimp export value this year of USD 3.15 billion accounted for 45 per cent of the total seafood export of Vietnam. Shrimp were exported to more than 90 markets, of which the top ten were the US, the EU, Japan, China, South Korea, Australia, Canada, ASEAN, Taiwan and Switzerland, accounting collectively for 95.4 per cent of the country's total shrimp export. Vietnam had almost ten per cent of the global aquaculture shrimp production this year. To meet the demands arising from food security and environmentally conscious consumers globally, 11.4 per cent of the total shrimp production was eco-labelled and certified by the agencies and standards, such as Best Aquaculture Practices (BAP), the Aquaculture Stewardship Council (ASC), GLOBALG.A.P. Aquaculture Standard, and, for organic products, Naturland.

Sources: Minh et al. (2001); Hai et al. (2014); Hai et al. (2015); Rurangwa et al. (2016); FAO (2017); VASEP (2017).

11.5 SUPPLY GROWTH

Figure 11.1 shows a strong growth in world aquaculture production. Let us reflect a little on the forces behind this development. What changes on the supply side have worked together to bring about such a result? In short, we can say that the supply curve has shifted outwards: more can be produced at a given cost, or the same quantity can be produced at lower cost per kg fish. Of course, demand has worked together with supply over time to realise the observed production. We shall return to the demand and market side in Chapter 12. For an example of cost reduction, see the case of salmon in Table 11.2, with an average production cost of 33.86 NOK per kg in 2016. Three decades before, in 1985, the corresponding cost was almost 90 NOK per kg, measured in 2016 value, and the production was about 50 thousand tonnes (Fiskeridirektoratet, 2017). Thus, the 2016 cost was about one third of the 1985 level and the production in this period increased by a factor of about 25. The salmon price has also come down (with some fluctuations) during this period, but in most years it stayed well above the average cost and made this industry one of the most profitable in Norway.

The production cost development of salmon is, however, more multifaceted than noted above. Production costs fell steadily from the start of the industry up to 2005. From 2005 to 2016, however, the costs have roughly doubled, measured in nominal values. Even though we consider inflation, the cost increase is just over 60 per cent. Increased feed costs and increased costs for monitoring, prevention and treatment of lice are the most important explanations for cost increases. Salmon lice (*Lepeophtheirus salmonis*) are a natural parasite on salmonids in saltwater in the northern hemisphere. The lice eat skin, mucus and blood on the fish, and can make large wounds if there are many of them on a fish. The lice costs are still high, at around 5 billion NOK a year, but the growth in lice costs has decreased (Iversen et al., 2017).

The close relationship between product price and costs is what one would expect in a competitive industry. In addition, we can often observe price cycles for biological production due to the time elapsing from the production decision being taken until the product can be harvested. The close relationship between price and production costs comes from industrial competition, because otherwise it would have had a higher capital return than in other parts of the economy. A reduction in production costs can lead to good profitability in the industry. This market signal to producers induces them to produce more, but when the industry collectively increases production, the price will fall unless demand increases sufficiently. Further decline in production costs makes it profitable to increase production even more, and the pattern repeats itself.

Aquaculture production of a particular species will be the sum of the production of all farms and can be discussed using a standard production function

$$x = f(q; z, \propto t) \tag{11.1}$$

where x is the quantity produced, q is a vector of production factors, z is a vector of external factors that are beyond the control of the farm but affect the growth, and αt is a vector of factors that change production technology over time t. Feed is the main aquaculture production factor for fed species (Table 11.2). Changes in this cost item therefore have a significant impact on the total production costs. Besides feed, recruits, labour and capital are important production factors. The external factors given by vector z are biophysical conditions such as weather, water (temperature, circulation and salinity), oxygen content and cleanliness of the water, predators and climate change, as well as institutional factors. It can be difficult to measure how good each of these resources is, but the fact that aquaculture actually takes place in a country indicates that it is well suited for such production. In Chapter 13, we will discuss how external environmental factors may affect aquaculture production and how production may affect the aquatic environment.

A large part of the cost reduction in the world's aquaculture industries is due to a bundle of innovations that have improved productivity. Productivity can be defined as the relationship between production and use of input factors (*x/q*). Productivity growth is then a change in productivity, or how much more one can produce with the same amount of input factors. We can also study productivity growth's impact directly by a cost function, based on cost minimisation for a given set of input prices, fish price, technology and external factors:

$$C = c(w; x, z, \propto t). \tag{11.2}$$

Here, *C* is the production cost, while *w* is a vector of input factor prices. An advantage of using a cost function is that it explicitly represents the effect of changes in input factor prices. Key sources of productivity growth and cost reductions in aquaculture farming include (1) technological innovations, (2) increased knowledge, (3) systematic breeding (research), (4) development of better and adapted feed, (5) input factor price reduction, (6) development of processing infrastructure, (7) export market access and development, (8) better utilisation of economies of scale and (9) good governance and supportive government policies (Phuong and Oanh, 2010; Asche and Bjørndal, 2011; Vassdal and Holst, 2011; Roll, 2013).

For aquaculture production, coastal land and water are the basic natural resources required. Let us for the sake of brevity call this resource 'aqua-land'. As an example, we specify and extend the production function (11.1) by including explicitly the production factors labour (L), capital (K) and aqua-land (N), to arrive at

$$x = f(L^{0.3}\, K^{0.3}\, N^{0.4}; z, \alpha t). \tag{11.3}$$

The technology of aquaculture fish production, including shrimp, molluscs, etc., in this example exhibits constant returns to scale (CRS), with the partial output elasticities of labour and capital both fixed (*0.3*), a little lower than the partial output elasticity of aqua-land that is assumed equal to *0.4*. A major research question in empirical studies of aquaculture farm productivity is the estimation of parameters of production functions and of the corresponding cost functions. Functions can be relatively simple, such as in equation (11.3), or more complex for productivity measures (Vassdal and Holst, 2011; Asche et al., 2013). CRS technologies implies that when inputs of the three factors of production are all multiplied by a factor of *k*, the output also multiplies by a factor of *k*. For example, if labour, capital and aqua-land are all increased by ten per cent, output of fish is increased by ten per cent. In other words, this particular production function of aquaculture fish is homogeneous of degree 1. For partial changes, output in this example increases by four per cent if aqua-land increases by ten per cent. For labour and capital, the production increase is three per cent if one of these inputs increases by ten per cent.

Increased factor productivity has been important for the aquaculture industry – in particular, feed factor productivity, since feed is such an important factor. We will come back to this in Chapter 14. One reason why the aquaculture industry portrayed in Table 11.2 has grown so rapidly is that labour productivity has also increased considerably and systematic breeding has caused the fish to grow faster. Note the relatively low cost share of labour in Table 11.2. The facilities have also grown considerably. Chemical treatment, vaccines and other disease prevention, oxygen supplies, etc. have contributed to overall aquaculture production growth across many countries and continents (Annex Table A14.1).

In contrast to these two success stories of Norway and Vietnam, with mainly continuous growth, fish diseases have heavily affected the Atlantic salmon in Chile. Production declined from 385 thousand tonnes in 2005 to 115 thousand tonnes in 2010, with the major reduction in just one year from 2008 to 2009. Both the Vietnamese pangasius and the Norwegian salmon export have at times experienced some setbacks in the US market due to American antidumping measures. Such import restrictions usually harm domestic consumers through higher retail prices, but rarely manage to offer lasting protection to the affected parts of their own aquaculture industry. (Nguyen, 2010; VASEP, 2017a; SEAFOOD, 2017).

Will aquaculture production continue to rise in the years ahead? Kobayashi et al. (2015) studied this important issue and concluded positively. Using a global, partial-equilibrium, multi-market model, they investigated what the global seafood market may look like in 2030. Based on observed regional trends in seafood production and consumption, the model projects that the total fish supply will increase from 154 million tonnes in 2011 to 186 million tonnes in 2030, with aquaculture entirely responsible for this increase, in particular for tilapia and shrimp. Nadarajah and Flaaten (2017) emphasise the need to improve the domestic infrastructure, such as electricity, irrigation and roads, to facilitate aquaculture production. Technology and skills transfer will increase aquaculture productivity. In addition, trade policies help to reduce price fluctuations and market failure and increase aquaculture value.

Annex Ch. 11

	Country	Production		Average annual change (%)	
		Quantity	Value	i^{qty}	i^{val}
1	China	60166.82	77412.90	8.87	10.42
2	India	5061.02	10612.68	7.09	10.05
3	Indonesia	15012.30	9670.64	12.58	11.29
4	Chile	1142.55	8586.29	16.52	22.86

	Country	Production		Average annual change (%)	
5	Viet Nam	3402.27	8207.86	11.03	12.72
6	Norway	1356.69	6441.34	12.70	12.44
7	Bangladesh	2008.67	5001.65	9.38	11.66
8	Japan	1062.54	4561.00	-0.39	1.97
9	Thailand	897.48	2453.12	6.60	10.30
10	Korea, Republic of	1621.96	2158.73	2.64	7.06
11	Ecuador	397.31	2132.20	8.34	7.50
12	Philippines	2342.88	2094.31	5.24	4.97
13	Egypt	1155.96	1927.92	11.71	15.33
14	Myanmar	981.94	1756.29	17.95	17.09
15	Brazil	569.72	1376.96	13.22	11.81
16	Taiwan	327.70	1292.04	0.93	2.45

	Country	Production		Average annual change (%)	
17	United Kingdom	210.77	1208.14	8.05	9.36
18	United States of America	423.58	1128.85	0.88	3.02
19	Iran	333.15	998.02	9.71	10.29
20	Turkey	236.63	949.19	15.22	16.51
21	Malaysia	513.99	936.95	7.17	12.02
22	Nigeria	314.98	899.46	12.59	15.99
23	France	205.55	892.43	-0.07	4.35
24	Australia	82.97	842.22	7.34	11.90
25	Canada	163.55	721.34	9.95	13.84
26	Mexico	202.92	671.73	9.76	14.03
27	Peru	103.12	609.81	9.78	10.53
28	New Zealand	100.57	607.89	7.26	15.88
29	Greece	105.39	552.90	12.52	14.61
30	Russian Federation	158.42	550.51	0.26	4.05
31	Spain	286.03	535.82	0.36	2.94
32	Italy	148.75	446.38	1.30	3.21
33	Uganda	114.31	280.83	27.27	34.50
34	Colombia	93.93	275.18	15.69	14.18
35	Honduras	58.42	237.85	15.72	15.72
36	Cambodia	131.53	227.14	13.48	13.66
37	Pakistan	149.77	223.26	9.56	9.77
38	Saudi Arabia	26.94	204.31	20.61	23.02
39	Lao	108.43	162.64	11.69	13.04
40	Ireland	35.42	157.30	3.18	9.23
41	Iraq	25.71	150.87	5.84	8.68
42	Denmark	37.63	144.02	1.51	3.19

	Country	Production		Average annual change (%)	
43	Korea, Dem. People's Rep	553.95	125.58	-0.87	-2.96
44	Poland	38.54	119.73	2.18	3.50
45	Nepal	45.7	119.32	9.52	12.53
46	Netherlands	62.98	118.38	-1.13	2.38
47	Costa Rica	24.63	117.55	17.10	19.49
48	Germany	27.97	100.75	-3.48	-0.96
49	Guatemala	21.40	98.13	14.70	13.68
50	Israel	20.51	93.50	1.72	5.14
51	Venezuela, Bolivarian Republic	24.82	93.50	11.31	13.93
52	Croatia	14.36	92.75	2.54	5.57
53	Tunisia	12.85	77.08	15.27	21.58
54	Sri Lanka	35.13	74.04	17.97	15.69
55	Nicaragua	27.56	66.10	23.78	20.54
56	Portugal	10.33	63.97	1.64	2.67
57	Finland	14.17	60.53	1.20	1.00
58	Iceland	8.43	55.67	14.17	14.56
59	Sweden	12.46	54.28	4.56	6.83
60	Ukraine	23.15	52.94	-4.35	-2.09
61	Panama	9.74	51.46	5.03	3.92
62	Ghana	41.58	50.60	15.45	16.10
63	South Africa	6.26	46.42	8.48	9.79
64	Czechia	20.17	46.03	0.17	-0.52
65	Cuba	30.55	40.82	6.38	7.61
66	Madagascar	19.07	38.12	14.62	14.77
67	Hungary	16.33	36.56	-0.21	3.28

Country		Production		Average annual change (%)	
68	Bulgaria	12.35	33.14	-0.06	1.61
69	Singapore	5.71	26.78	5.24	7.27
70	Belarus	9.89	25.31	-1.43	1.10
71	Romania	10.86	24.91	-4.64	-4.94
72	Austria	3.45	24.62	-0.54	2.90
73	China, Hong Kong	3.90	21.17	-2.45	-0.12
74	Syria	2.75	9.05	0.41	2.56
	Total 74 countries	103051.87	162359.78		
	Global total	103544.49	164942.09		

Table A11.1 Aquaculture production 2015, in quantity (thousand tonnes) and value (million USD), as well as the average annual change in the period 1985–2015. 74 countries ranked according to value.

Notes:
*Aquaculture quantity (in thousands tonnes) and value (million US$) is the average for 2014 and 2015.
* Countries are ranked based on value (average aquaculture value 2014–2015).
* For Saudi Arabia i^{qty} and i^{val} for the period 1986–2015,
* Czechia (this is the new name for Czech Republic) i^{qty} and i^{val} for the period 1993-2015.
* Venezuela; average price (2012_2013) for an unit aquaculture production ($99.23*10^6$) / ($26.35*10^3$) = 3766.98usd/ton So for 2014_2015: 24820 * 3766.98=$93.496*10^6$ USD

Sources: FAO (2016); Nadarajah. S. and O. Flaaten (2017); Nadarajah. S., UiT – The Arctic University of Tromsø, personal communication.

12 DEMAND AND TRADE

12.1 CONSUMER DEMAND

Fish and other aquatic species provide animal protein and valuable nutrients, such as the long-chain omega-3 fatty acids DHA and EPA – important for optimal neurodevelopment in children and for improving cardiovascular health and growth of humans (see Box 2.2). The attitudes and preferences of consumers seem to be leading more and more in the direction of healthy food, including fish products. The existence and increasing use of eco-labelling, a form of certification programme, for aquaculture fish is an indicator of the gradual change in consumer attitudes. There is increasing concern for both product safety and the desire to avoid the negative environmental and socioeconomic effects caused by aquaculture (pollution, disease incidence, social conflict) and to improve its sustainability. Fish is highly perishable and can spoil more rapidly than most other food. Therefore, thorough post-harvest handling is important to maintain quality and nutritional attributes, and to avoid waste and losses. Often, such handling is easier and less costly in aquaculture than in capture fisheries due to the producers' control of the production process and the products.

In recent years, many aquaculture countries have adopted certification to ensure that their farms operate in an environmentally friendly manner. Some of the countries included in Annex Table A11.1 practise ecolabel certification and others do not. Best Aquaculture Practices (BAP) and Aquaculture Stewardship Council (ASC) certification are among the most widespread eco-label certifications. The Global Aquaculture Alliance, focusing on environmental, social, food safety, and traceability issues, developed the BAP standard. This certification programme was implemented through the Aquaculture Certification Council, an agency that provides certification licenses to the entire aquaculture production chain, including hatcheries, farms, and seafood processing plants. The agency inspects all practices and product quality, and reviews records. The ASC, founded in 2010, aims to transform aquaculture toward environmental sustainability and social responsibility. The ASC provides standards for the farmed seafood chain. The standards for certification were developed and implemented in accordance with the International Social and Environmental Accreditation and Labelling Alliance (ISEAL) guidelines. Changes in subjective preferences, relative prices, and income, in addition to production costs and supply, contribute to the dynamic development of the global markets for fish and fish products. Of course, institutional trade arrangements, such as tariffs and non-tariff barriers to trade, also play an important role.

The share of world fish production used directly for human consumption has increased from 67% in the 1960s to 87% in 2014. Most of the remaining 13%, or 21 million tonnes, was used for non-food products, including about three-quarters for reduction to fishmeal and fish oil. Other non-food uses are in aquaculture (feed and fingerlings/recruits), bait, pharmaceutical production, livestock and fur animals. In 2014, almost half of the production for direct human consumption was live, fresh or chilled fish, which are usually the preferred and highest priced forms. In pre-industrial times, and even more than one thousand years ago, dried fish was used in long-distance and international trade, including fresh-water fish in China and the white fish cod in Norway and other parts of Europe. In present day trade, freezing is the most common method for the conservation of fish, and in 2014, this amounted to more than a quarter of all capture and aquaculture fish production. The increase in frozen products is a result of both technological development of the distribution chains from producers to consumers and the consumers' change in attitudes and preferences for this type of fish products.

12.2 DEMAND AND PRICE DEVELOPMENT

We have seen that aquaculture production and trade have expanded in many countries over the last decades, as well as globally. Was this increase possible only at the expense of lower product prices, or has the industry managed to maintain prices as quantity expanded? We will use both market theory and a couple of examples, pangasius in Vietnam and salmon in

Norway, to discuss these issues. From theory and empirical research, we know that subjective preferences, relative prices, and income, in addition to availability, determine the consumer's demand for a particular aquaculture product, as well as for other goods and services. Figure 12.1 shows three demand curves, D_1, D_2 and D_3 for a given product. Recall that with the subjective (preferences) and objective (prices and income) factors behind the market demand curve, all three curves show a negative relationship between price (P) and quantity (Q) of the product. The curves could illustrate demand at three different time periods, with D_1 as the oldest, or for three different markets; local, national and international – from D_1 to D_3. Correspondingly, the supply curves in Figure 12.1 may represent three different time periods (years), or supply from producers locally, nationally or globally.

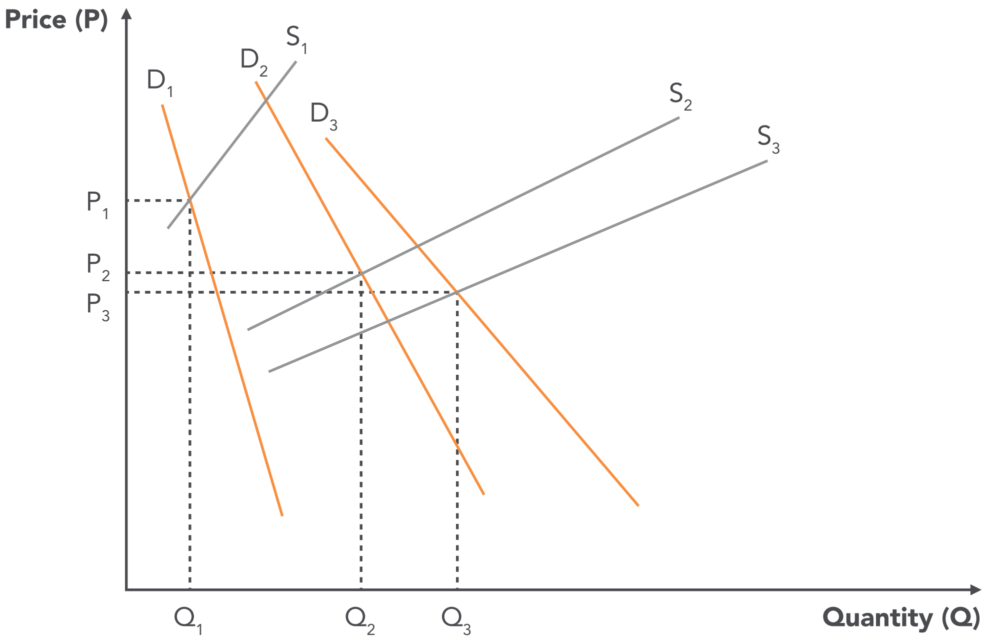


Figure 12.1 Expansion of supply and demand of an aquaculture product, with quantity increase and price decline over time.

On the commencement of the modern pangasius industry in Vietnam, around the year 2000, supply could have been like S_1 and demand as D_1 in Figure 12.1, with a relatively high price, P_1, and low quantity, Q_1, mainly locally and nationally. Then higher income of people, domestically and internationally, increases demand to D_2. This could have resulted in a market price above P_1, at the intersection (S_1,D_2). However, technological development and other cost saving arrangements may have reduced the production cost per kg, shifting the supply curve to the right, to S_2. This would result in a lower price and larger quantity produced and exported, at (P_2,Q_2). With the same reasoning, further development could lead to the price–quantity combination (P_3,Q_3). Note on the graph the relatively small quantity expansion from Q_2 to Q_3 compared to Q_1 to Q_2, and the small price decrease from P_2 to P_3.

The current development in export quantity and price of Vietnamese pangasius is shown in Figure 12.2 for the period 2000–2017. The upward sloping uppermost curve is the total production in metric tonnes, increasing from about 0.1 million tonnes (round weight) in the year 2000 to about 1.25 million tonnes in 2017. The export quantity is smaller than production partly due to some domestic consumption and partly due to processing and the product weight of export goods. In the first part of the period, the average export price fell, though with some ups and downs, from about 3.75 USD per kg in 2000 to 2.3 USD per kg in 2008, and this corresponds to a movement from (P_1,Q_1) to (P_2,Q_2) in Figure 12.1. The demand curve shifted to the right and the supply curve shifted downward, implying a price decrease and a quantity expansion. After about 2008, Figure 12.2 shows that the quantity increase slowed down and the export price more or less stabilized, almost as a movement from (P_2,Q_2) to (P_3,Q_3) in Figure 12.1.

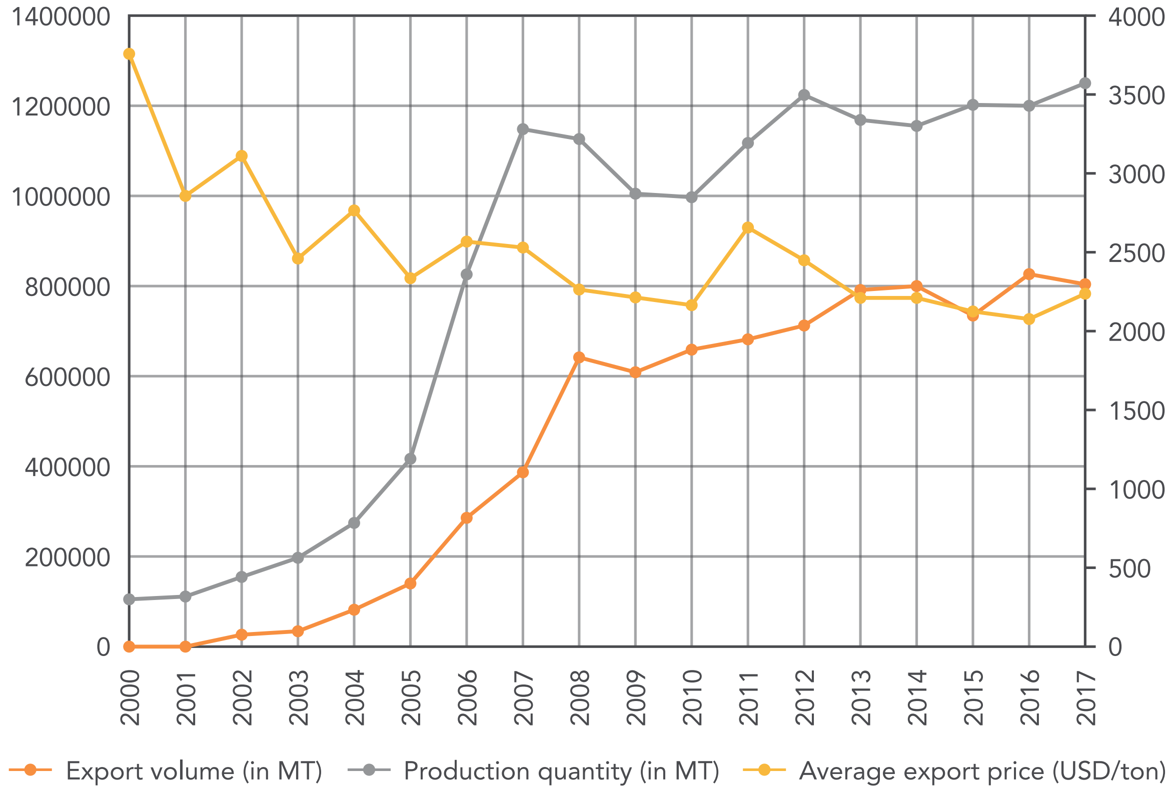


Figure 12.2 Pangasius production and export, Vietnam 2000–2017.
Sources: VASEP (2017); Duy Nguyen Ngoc, PhD, Lecturer, Nha Trang University, personal communication.

The quantity-price development illustrated in Figure 12.1 is, of course, just one of countless possibilities. Another one is shown in Figure 12.3, where demand shifts relatively more than supply from period two to three and both quantity and price increase. Also, note that if the supply curve had not shifted downward from S_2 to S_3, the price increase would have been even higher at the intersection (S_2,D_3), at the expense of a somewhat lower quantity than Q_3. Recall that the supply curve is determined by several factors, such as production technology and input prices. We will see that the theoretical pattern discussed in Figure 12.3 may help understand the aquaculture growth of salmon in Norway.

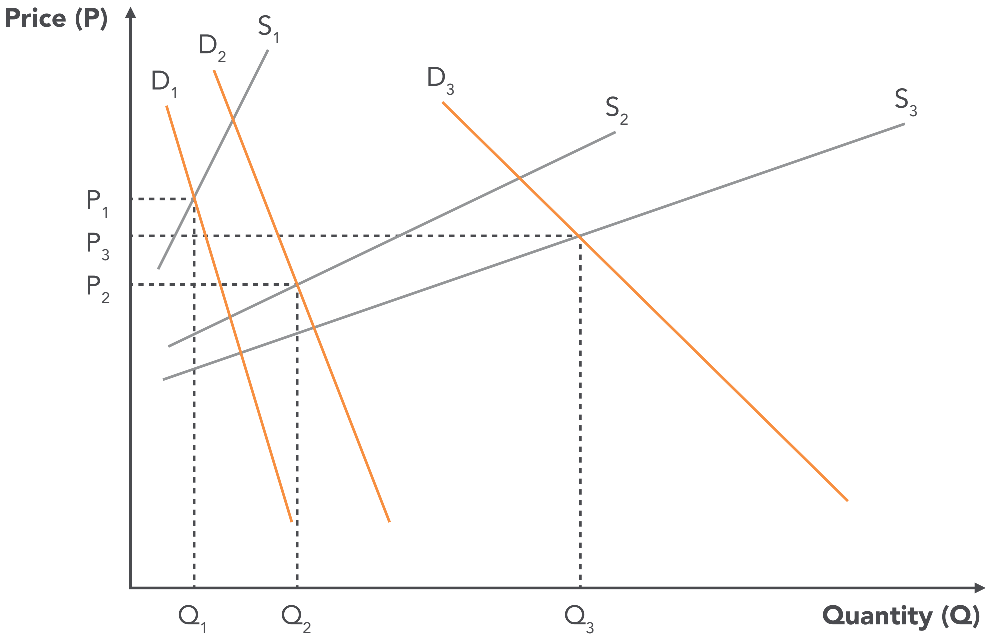


Figure 12.3 Expansion of supply and demand of an aquaculture product, with quantity and price increase in the last period.

The current development of Norwegian export of Atlantic salmon is shown in Figure 12.4 for the period 1981 to 2016. The quantity increased from hardly anything in 1981 to about one million tonnes in 2012–2016. This is product weight; the farm gate quantity in each of the years 2014 to 2016 was 29 percent higher, due to some domestic consumption and the round weight measure at the farm gate. For Vietnamese pangasius in Figure 12.2 the production quantity in 2014–2016 is about 50 percent higher than export, mainly reflecting a higher share of fish fillets in export than for salmon. The latter is often exported as gutted, but with head on, with less reduction in product weight than for fillets. However, recall that both price and quantity are scaled differently for salmon and pangasius, with the price of the former much higher than that of the latter (see Table 11.2 for recent prices).

The salmon export price fell from about 7.0 USD per kg in 1981 to 3.3 in 2001, while quantity increased significantly. We can say that in the first 20 years of salmon export the quantity increase was made possible through a price reduction. At the same time the farm productivity increased and the industry could cope with a lower price. However, Figure 12.4 also demonstrates that in 2001 the market price, in USD, started increasing and is now (2016) at a higher level than at the commencement of the aquaculture salmon industry, despite the continued quantity expansion. The price is in nominal USD, but adjusting for inflation would not alter the main picture described.

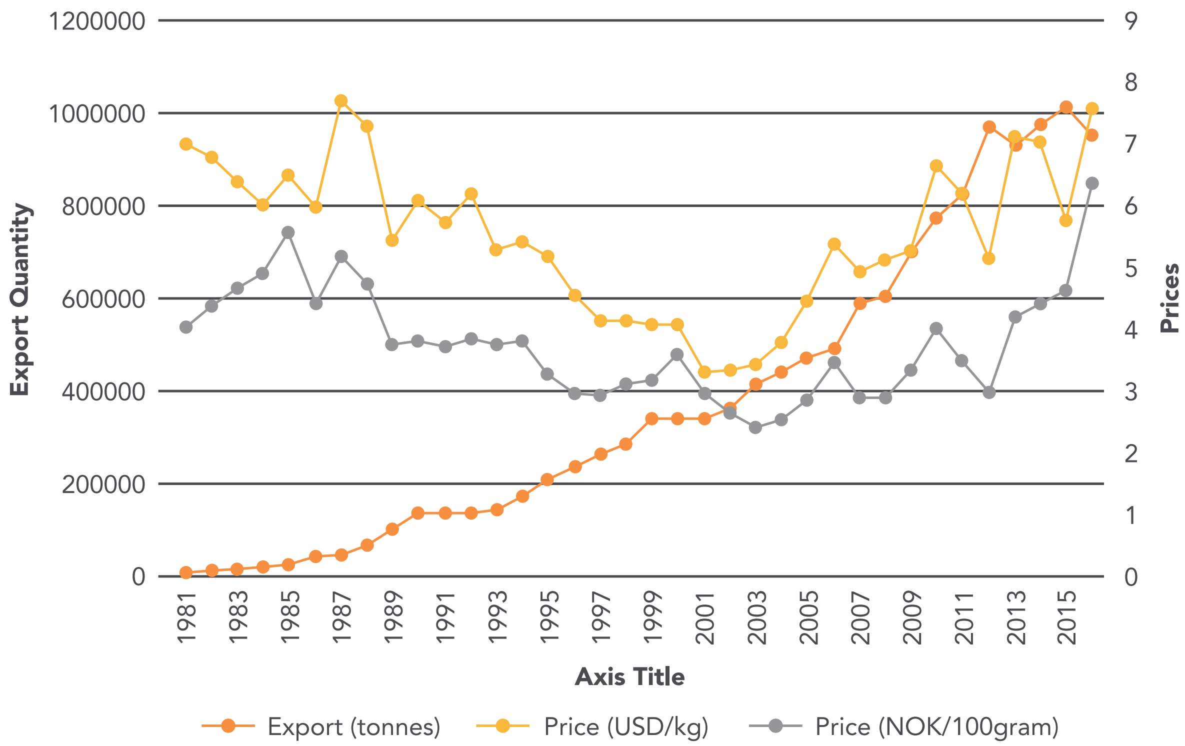


Figure 12.4 Atlantic salmon export, Norway 1981–2016
Source: Statistics Norway

For aquaculture salmon in Norway, empirical research for 1996–2011 shows that productivity growth has slowed down over the years, indicating that demand growth is the main driver of production growth (Asche et al., 2013; Brækkan and Thyholdt, 2014). Recent research by Iversen et al. (2017), discussed in subchapter 11.5, has found increased production cost per kg salmon from 2005 to 2016, mainly due to the increased cost of feed and parasite (lice) protection. Using Figure 12.3 as an illustration, we could say that the demand curve has shifted to the right, but at the same time the supply curve S did not shift downward, but rather upward in the last decade. Thus, increased demand for Atlantic salmon globally over the last fifteen years has been the main driver of price and quantity, despite a production cost increase in the last decade. Norway has more than half of the world aquaculture production of salmon and it is likely that the other producer countries, including Chile, UK and Canada, also have experienced a cost increase, since all producers depend on internationally traded feed that is the major cost component (Table 11.2) of most aquaculture. Salmon production in Norway is largely limited by the licensing system, which could have been illustrated by a vertical supply curve S_4 in Figure 12.3. This will be further discussed in chapters 13 and 14.

12.3 INTERNATIONAL TRADE IN AQUACULTURE PRODUCTS

In 2017, the world population is estimated at 7.6 billion. It is a critical challenge to feed the growing world population, expected to reach 9.8 billion and 11.2 billion by 2050 and 2100, respectively (UN, 2017). Not just to feed, but to provide good tasting and nutritional quality food is achievable only through increased food production and reduced food waste. This will require more resources for food production, such as land and water, and these are becoming even scarcer in a more crowded world. Further growth in aquaculture production and trade can provide some of the required food increase needed (Kobayashi et al., 2015).

For a thorough discussion of the aquaculture trade and the potential for further growth we would need to use elements from several fields of economics, such as natural resource economics, economic development theory, and international trade theory, as well as aquatic biology and business economic subjects. However, let us be less ambitious for now and limit the discussion to why some countries could expand aquaculture production and export while others mainly increase the import of seafood. Fish and fish products top the world trade in food products. This leads us to international trade theory, a sub-field of economics, analysing the patterns of international trade, its origins, and its welfare implications. A country's economic factor endowment is commonly understood as the amount of land, labour, capital and entrepreneurship that a country possesses and can exploit for manufacturing. Countries with a large endowment of resources tend to be more prosperous than those with a small endowment, all other things being equal. The development of sound institutions to access and equitably distribute these resources is usually considered necessary for a country to obtain the greatest benefit from its factor endowment. However, for aquaculture production also countries without the best institutions have succeeded in developing this industry (Nadarajah and Flaaten, 2017).

In general, relative endowments of the factors of production (land, labour and capital) determine a country's comparative advantage. Countries have comparative advantages in those goods for which the required factors of production are relatively abundant locally. For aquaculture production, coastal land and water, called aqua-land, are the basic natural resources required. Throughout the history of economic thought, several theories and models of international trade have been developed to explain and predict trade patterns. The Ricardian model of comparative advantage has trade resulting from differences in labour productivity using different "technologies". Later, the widely known trade theory by the Swedish economists Heckscher and Ohlin (H–O), in the 1930s, did not require production technology to vary between countries, so (in the interests of simplicity) the H–O model has identical production technology everywhere. Ricardo considered a single factor of production (labour) and would not have been able to produce comparative advantage without technological differences between countries; all nations would become autarkic at various stages of growth, with no reason to trade with each other. The H–O model introduced variable capital endowments, creating endogenously the inter-country variation of labour productivity that Ricardo had imposed exogenously.

What about aquaculture production? How to explain that some countries produce and export huge quantities whereas others hardly produce, but import fish and fish products? In the simple H–O model (see any text in international trade theory or Wikipedia), now adapted in Figure 12.5 to our purpose, both countries produce two commodities, say aquaculture fish on the one hand and all other goods on the other. Each commodity in turn is made using two factors of production. Two identical countries (A and B) with respect to preferences have different initial aqua-land endowments and other resources, allowing the maximum production of fish, X^A and X^B and other goods Y^A and Y^B, as shown in Figure 12.5. The autarky equilibrium is at (A^A, A^B), with no trade, and production equals consumption in each country. With trade, the consumption equilibrium is (C^A=C^B); both countries consume the same bundle of fish and other goods beyond their own Production-possibility frontier; production and consumption points for each country differ. With trade, country A produces more aquaculture fish than it consumes, the quantity on the X axis corresponding to P^A minus the quantity corresponding to C^A. The export of country A equals the import of country B and the consumption of aquaculture fish is the same in the two countries, which both reach a higher welfare than in autarky without trade. Both exporters and importers gain from production specialization and trade.

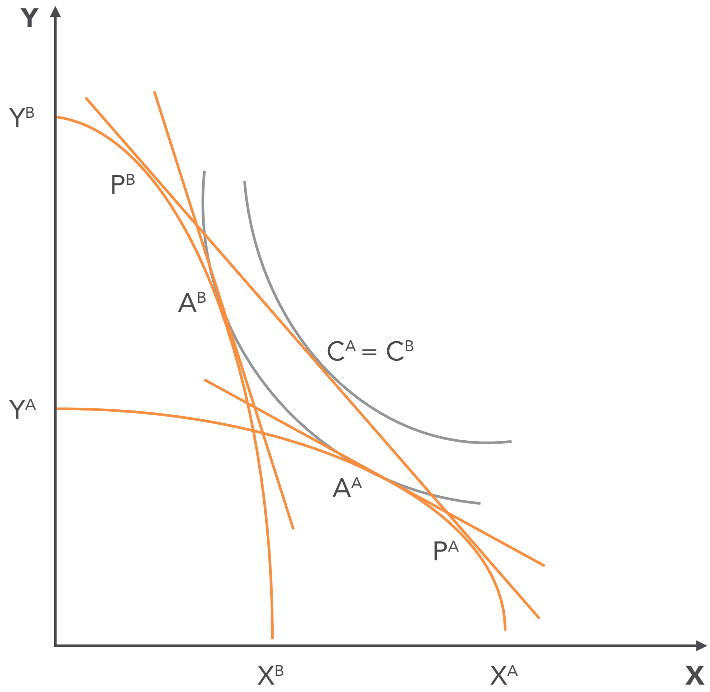


Figure 12.5 The Heckscher-Ohlin model in two goods and two countries.

12.4 FISH TRADE

It is difficult to disentangle trade statistics for capture and aquaculture fish on a global scale. Even though national trade statistics of major fisheries countries could be helpful, it is outside the scope of this book to go into such details. The FAO works continuously to improve statistical databases and make them more easily accessible (FAO, 2016; FAO, 2017a) and we will use mainly these sources, as well as the quarterly *FAO Globefish Highlights* on the world seafood markets to give an overview of some fish trade patterns (http://www.fao.org/in-action/globefish/publications/en/). We have seen that total fish production has increased for several decades, and since the 1990s mainly because of a rise in aquaculture. Trade increases even more; export rises from 25% of world fisheries production in 1976 to about 36% in 2014, on a quantity basis. World trade in fish and fishery products has grown significantly also in value terms from 1976 to 2014 with annual growth rates of 8.0% and 4.6%, in nominal and real terms, respectively, reaching USD 148 billion. This is due to mainly better conservation methods in the transport and trade of perishable goods, an increase in consumers' purchasing power and desire for greater food variety, as well as reductions in tariffs and technical barriers to trade in fish products. Over the last few decades, tariff protection has been gradually reduced; through unilateral liberalization and as a result of bilateral and regional trade agreements (Bellmann et al., 2016).

The top ten exporters and importers of fish and fishery products are shown in Table 12.1, in relative value figures. China is by far the largest exporter, and is the third biggest importer. This mix is due partly to the import of raw material, including white fish, for processing and re-export, and partly to balance the species and product mix demand domestically compared to trade. Annex Table A11.1 shows that China is by far the largest aquaculture producer, both in quantity and value terms. In value, it is more than seven times as big as the producer rated second, India, and in quantity, China is about four times as big as the second, Indonesia. The latter has a relatively large production of cheaper aquatic plants (Table 11.1) – in value terms Indonesia is only one eighth of China. Aquaculture products dominate the Chinese fish export (FAO, 2016).

It is interesting to see in Table 12.1 that the second largest exporter (value) is a tiny country, Norway with 5.2 million people, compared to China's 1,400 million. Referring to the discussion above, the comparative advantage of Norway is a relatively huge EEZ, for wild fish, and very good access to aqua-land, for high value salmon production. Vietnam and Thailand follow Norway as exporters. These two countries are among the largest aquaculture producers (Table A11.1) and this is reflected in their export of shrimp, tilapia and pangasius.

Chile is one of the major producers and exporters of Atlantic salmon, but fish diseases have often set back the production. Despite this, the average annual growth over the years 2004–2014 is above the average of the top ten exporters. The United States of America is, in addition to China, a country appearing in the top ten for both export and import. But its import share is 3.5 times higher than the export share, indicating the strong purchasing power and seafood preferences of American consumers.

The seventh largest exporter, India, has about the same population as China, but even as the second largest aquaculture country, it has only just above one seventh of the Chinese aquaculture production in value terms (Table A11.1). A significant part of India's export is high value shrimp, and Table 12.1 shows that it is not among the ten largest importers, despite its huge population. Also, note that India is number one in annual average growth in export value for 2004–2014; mainly due to its valuable shrimp production for export (Navghan and Kumar, 2017).

On the import side, the top ten list is dominated by wealthy and partly populous countries; however, China and Korea are not among the richest countries on a per capita scale. The other eight are USA, Japan and some EU countries, all belonging to the rich, developed countries with a long history of seafood consumption.

Exporters	Percentage share	APG*		Importers	Percentage share	APG*
China	14.2	12.2		USA	14.4	5.4
Norway	7.3	10.1		Japan	10.6	0.2
Vietnam	5.4	12.6		China	6.0	10.5
Thailand	4.4	4.9		Spain	5.0	3.0
USA	4.1	4.8		France	4.7	4.8
Chile	4.0	8.9		Germany	4.4	8.3
India	3.8	14.8		Italy	4.4	4.7
Denmark	3.2	2.9		Sweden	3.4	13.9
Netherlands	3.1	6.4		United Kingdom	3.3	5.1
Canada	3.0	2.6		Republic of Korea	3.0	6.6

Exporters	Percentage share	APG*		Importers	Percentage share	APG*
Top ten subtotal	52.5	8.5		Top ten subtotal	59.3	4.8
Rest of the world total	47.5	6.5		Rest of the world total	40.7	9.3
World total	100.0	7.5		World total	100.0	6.4
World total USD millions	**148 148**	**-**		**World total USD millions**	**140 615**	-

Table 12.1 Top ten exporters and importers (value) of fish and fishery products, 2014.
*Average percentage annual growth 2004–2014.
Data source: FAO (2016).

On a global basis some regions dominate the surplus fish export value, mainly China, Oceania, Latin America and the Caribbean, whereas Canada, USA and Europe are the dominating export deficit regions. Africa used to be a deficit region, but a surge in export value in the last decade has put it into a neutral position with about 6 billion USD in both export and import value of fish and fishery products. Dividing the world into developed and developing countries reveals that the former on average import seafood at an average price, in USD per kg, that is twice that of developing countries. This reflects the combined differences in food preferences and income between "rich" and "poor". (FAO, 2016)

We have seen that capture fish production has stagnated whereas aquaculture production has expanded over the last couple of decades. Thus, aquaculture products have become more plentiful than capture fish, especially considering population growth. When supply meets demand we should, on this background, expect a greater increase in capture fish prices than aquaculture fish prices. In fact, the FAO fish price index supports this, with an increase in the capture index of about 80% against about 35% for aquaculture, from January 1990 to January 2016 (FAO, 2016).

12.5 TRADE IN MAJOR FISH SPECIES

Trade in fish and fishery products has increased more than the global production, becoming more complex with greater diversification among species and products. A significant share of the fishery trade consists of high-value species, such as salmon, shrimp, tuna, cod and other ground fish. Cheaper species, such as small pelagics are traded in large quantities, and exported to low-income consumers in developing countries. As noted above, fish trade statistics have some weaknesses when it comes to the breakdown of information on species and type of processing. However, for our purpose the FAO's database contains sufficient time series, groups of species as well as countries of origin and of destination, both for value and quantity. The dramatic expansion in aquaculture production has contributed significantly to increased trade in species that used to be primarily wild caught; with farmed species and types of products representing a growing share of international fish trade. The exact breakdown between products of capture fisheries and aquaculture in international trade is still open to discussion. Estimates indicate that aquaculture products represent between 20–25 percent of traded quantities and 33–35 percent in value terms, indicating that an important segment of the industry is export focused. If only fish products for direct human consumption are considered, the quantity share increases to 26–28 percent and the value share to 35–37 percent (FAO, 2016).

The rise of aquaculture has had a strong impact on logistics and distribution, reducing the cost of distribution due to economies of scale, and has enabled farmed seafood to create new markets for consumers all over the world. This is especially the case for fresh and chilled products where both regional distribution by truck and international transport by air, especially of fillets, have reached markets and consumers with regular supplies of farmed products. The distribution of frozen aquaculture products has also expanded dramatically, enabled by increased volumes and reduced transportation costs.

The degree of integration between wild and farmed fish has been analysed, but there is not full analytic consensus on whether farmed fish prices will always respond to those of wild fish or vice versa, and whether one gets a natural premium (Asche et al., 1999; Asche et al., 2015; Bjørndal and Guillen, 2017). This may vary with market, species and product form. However, some heavily traded species such as salmon appear to display a significant degree of integration in terms of prices (see above). Increased supply from aquaculture has been a major influencing factor in price trends.

Due to their high perishability, 92 percent of trade in quantity terms (live weight equivalent) in fish and fishery products consisted of processed products (i.e. excluding live and fresh whole fish) in 2014. Fish is increasingly traded as frozen food (40 percent of the total quantity in 2014, compared with 22 percent in 1984). In the last four decades, prepared and preserved fish, including many value-added products, have doubled their share in total quantity, increasing from 9 percent in 1984 to 18 percent in 2014. Notwithstanding their perishability, trade in live, fresh and chilled fish has increased due to consumer demand and represented about 10 percent of world fish trade in 2014, also thanks to innovative chilling, packaging and distribution technology. In 2014, 78 percent of the quantity exported consisted of products destined for human consumption. Much fishmeal and fish oil is traded because, generally, the major producers (South America, Scandinavia and Asia) are distant from the main consumption centres (Europe and Asia) (FAO, 2016).

Table 12.2 gives an overview of the major groups of species in world trade in 2015. Salmon, trout and smelts now have the highest value share of the commodity groups. This has increased over time, from 6.6 percent in 1981, to 16.6 in 2013 and 16.4 percent in 2015, thus stagnating in the last few years. Overall, demand and trade has grown steadily, in particular for farmed Atlantic salmon (Figure 12.4). Prices of farmed salmon have fluctuated during the last few years (2014–2017), but overall remained at high levels. "High price levels, in particular for Norwegian salmon, which is expected to represent a growing share in major markets. In contrast, in Chile, the second major producer and exporter, the salmon industry is facing falling prices and higher production costs than most other producing countries, with Chilean aquaculture companies incurring substantial losses in 2015" (FAO, 2016). However, this author thinks the price differences mainly reflect quality, production cost and cost-insurance-freight (cif) differences, but this remains to be analysed (suggestion for MSc thesis, dear students!). Aquaculture salmon meets market competition from catches of wild Pacific salmon, in particular from Alaska and British Columbia. Plentiful harvests in a rather short season tend to drive down prices for all the major wild-caught salmon species. For the future salmon markets, it will be interesting to see how consumers receive genetically modified salmon (approved in 2015 by the Food and Drug Administration of the United States of America); will it get a price premium or loss compared to wild and traditional aquaculture salmon?

Main commodity group	Share by value (%)	Share by quantity (%)	Average price (USD/kg)	ISSCAAP group code number
Fish	**65.3**	**79.4**		
Salmons, trouts, smelts	16.4	10.0	5.93	23
Tunas, bonitos, billfishes	8.8	9.6	3.32	36
Cods, hakes, haddocks	10.0	12.5	2.89	32
Herrings, sardines, other pelagic fishes	6.7	17.3	1.40	35, 37
Flounders, halibuts, soles	2.0	1.9	3.87	31
Other marine fishes	16.7	23.9	2.52	24, 25, 33, 34, 38, 39
Tilapias and other cichlids	1.3	1.4	3.51	12
Carps, barbels and other cyprinids	0.2	0.3	2.53	11

Main commodity group	Share by value (%)	Share by quantity (%)	Average price (USD/kg)	ISSCAAP group code number
Other freshwater fishes	3.2	2.6	4.46	13, 21, 22
Crustaceans	**22.5**	**9.4**		
Shrimps, prawns	15.5	7.2	7.82	45
Crabs, king crabs, lobster	6.4	1.8	13.18	42, 43, 44
Other crustaceans	0.6	0.4	4.78	41, 47
Molluscs	**10.6**	**9.3**		
Squids, cuttlefishes, octopuses	6.1	6.2	3.51	57
Bivalves	3.2	2.4	4.92	53, 54, 55, 56, 81
Other molluscs	1.2	0.7	6.41	52, 58
Other aquatic animals and plants	**1.6**	**1.9**		64, 76, 77, 82, 83, 91, 92, 93, 94
Total	**100**	**100**		
Value (Billion USD) and Quantity (Million tonnes)	**133.34**	**36.91**	3.61	

Table 12.2 Shares of main groups of species in world fish trade (export), 2015
Sources: Data from FAO, 2018; Nadarajah. S., UiT – The Arctic University of Tromsø, personal communication.

Shrimp now ranks second in value terms, Table 12.2, after having been the most-traded product for decades. Shrimp, including prawn, are mainly produced in developing countries, and much of this is exported. However, as economic conditions improve, growing domestic demand in these countries may lead to lower export. In addition, decreases in aquaculture farms in some Asian countries caused a decline in output, although global farmed shrimp production has increased. Global shrimp prices have fallen significantly year-on-year since the surge in aquaculture production in the 1980s. Real prices in USD more than halved until early in this century, displaying a pattern much like pangasius and salmon discussed above (see Figures 12.1–12.4), with decreased price for the global market to accept the increased quantity. However, in the last decade price levels have flattened, and in some cases even increased somewhat (FAO, 2016). In the short term, shrimp prices have often displayed fluctuating behaviour. For example, "in the first half of 2015, shrimp prices plummeted by 15–20 percent compared with the first half of 2014, as a result of the supply and demand disparity in the United States of America, the EU and Japan. Lower prices have hit export revenues and negatively affected margins for producers in many developing regions." (FAO, 2016).

Whitefish species, such as cod, hake, saithe and pollock are mainly wild caught and amount to almost ten percent of the world seafood export (Table 12.2). Among these the more expensive cod is often exported to low labour cost countries, such as China and Vietnam, for processing and re-export. Cod has remained one of the most expensive whitefish, despite experiencing strong competition from aquaculture species. Farmed whitefish species, such as tilapia and pangasius, at lower price, have entered traditional whitefish markets and enabled the sector to expand substantially by reaching new consumers. In Table 12.2, pangasius, usually registered as catfish, is included in the commodity group "Other freshwater fish". Whereas cod has been internationally traded for more than a thousand years, pangasius is a relatively recent species in global trade, but is now exported to about the same number of countries. "Steady demand from across the globe for this relatively low-priced species is expected to drive its production development in other producing countries, particularly in Asia. In the last two years, demand has remained strong in the United States of America, the largest market, as well as in Asia and Latin America. In contrast, imports into the other major market, the EU, have shown a downward trend". (FAO, 2016)

In Table 12.2 we see that carps and tilapia have value shares of 0.2 and 1.2 percent, respectively, of the world total export of these species. Compare this to the global production of 30,645 million tonnes of carp, including barbels and other cyprinids (Figure 11.2), and 6,380 million tonnes of tilapia, including other cichlids (Figure 11.4). Even though tilapia products on average are higher priced than carps (Table 12.2), this explains just a minor part of the production-export anomaly of these two groups. The major reason is probably that carps are produced mainly for local and national consumption and to a lesser extent than tilapia enter into international trade. The United States of America, the largest market for tilapia, imports mainly frozen products from countries in Asia and fresh products from Central America. This pattern with long distance supplies of frozen products and short distance supplies of fresh/chilled products can also be seen for other species than tilapia. However, on a global scale more moderate quantities of high value products, such as fresh/live lobster, red king crab and salmon, can be air transported at rather high transport cost and still be competitive.

About fifteen species of tuna are caught in the world oceans, varying in maximum size from a couple of kilograms for the smallest to more than 600 kg for the biggest. Mainly two types of product groups are entering the international trade, canned and frozen, as well as fresh. Fresh and frozen fetches the highest price, in particular for the sashimi tuna market in Japan. However, in 2015, for the first time in history, imports of air-flown fresh tuna to the USA were higher than those of Japan. Different paths in economic development and exchange rates cause this development. The high prices for big tuna species, such as Atlantic blue fin tuna (*Thunnus thynnus*), led to overfishing and reduced catches, spurring development of tuna aquaculture. Tuna fattening and farming operations still rely primarily on wild-caught juveniles that are fattened by use of small pelagic fish and dry feed. Tuna products from aquaculture have gradually over the last couple of decades entered international trade; for valuable fresh products mainly for the sashimi markets in Japan and the USA. Spain, Italy and Japan remain the largest consumers and importers of these species. Benetti et al. (2016) give a good overview of the development of the tuna aquaculture industry that is expanding in several countries.

Fishmeal and fish oil are very important ingredients in fish feed and are heavily traded as commodities internationally. With annual oscillations mainly caused by El Niño phenomena, fishmeal production has declined gradually since 2005, while overall demand has continued to grow, pushing prices to historic highs through late 2014 and 2015. Peru and Chile are the main exporters, and record low volumes in 2015 in both countries were the main reason for the historic price records (FAO, 2016). Fishmeal and fish oil prices both quadrupled, in USD, in the first fifteen-year period of this century. Such a strong increase is rare in commodity markets, and the FAO expects fishmeal and fish oil prices to remain high in the long term because of sustained demand, including from aquaculture. Note that fishmeal and – oil do not appear as separate trade categories in Table 12.2; in the export statistics they are included in the species they are produced from. Referring to Figures 12.3 and 12.4, where we discussed the price-quantity development of salmon in Norway, fishmeal and fish oil are products where demand is growing relatively faster than supply, leading to price increases to equalize supply and demand. In fact, the supply increase of small pelagics, the traditional input to the world fishmeal and oil industry, is very hard to achieve in capture fisheries due to ecological constraints. Thus, the supply curve for fish meal and oil, in a figure like Figure 12.3, will be more or less vertical, shifting back and forward with El Niño and other natural phenomena, as well as with biological overfishing or successful management of key stocks. The limit to marine meal and oil production and its effects on aquaculture production has been debated in the literature (Olsen and Hasan, 2012). A prediction from our analysis is that aquaculture species dependent on feed with a high content of marine meal and oil will continue to face cost increase. Since such species, including salmon, are popular with consumers, population and income growth globally may lead to continuing real price increase. However, substitution of marine ingredients in the feed by cheaper plant ingredients may slow the price increase of aquaculture fish.

13 ENVIRONMENTAL ISSUES

13.1 SOME PROBLEMS

Let us start this chapter by referring to two examples of aquaculture production decline. Thailand is one of the major farmed shrimp producers. Production dropped from an all-time high of approximately 600,000 metric tonnes in 2011 to less than 200,000 in 2014, a reduction of two thirds in only three years. Chile is number two of the Atlantic salmon producing countries. Production was reduced from 385 thousand tonnes in 2005 to 115 thousand tonnes in 2010, a decline of seventy percent in five years. In both cases, fish diseases played a major role. Modern aquaculture provides effective means for intensive seafood production under more or less controllable conditions. This major food growth industry, however, has experienced some relatively severe disease problems owing to lack of control of the microbiota in cultivation systems, as these two examples demonstrate. In the aquatic environment, the close relationship between bacteria, viruses, and parasites on the one hand, and their hosts in open production systems on the other hand, adds to this challenge. The use of vaccines and other health control means have so far kept most diseases under relative control, and, fortunately, antibiotic usage in aquatic ecosystems is presently kept to a minimum.

Infectious diseases are common in the ocean. Lafferty et al. (2015) tabulate 67 examples from around the globe that can reduce commercial species' growth and survivorship, or decrease seafood quality. Further, these impacts seem most problematic in the stressful and crowded conditions of aquaculture, which increasingly dominates seafood production. For instance, marine diseases of farmed oysters, shrimp, abalone, and various fishes, particularly Atlantic salmon, cost billions of dollars each year, according to Lafferty et al. (2015).

Through the water, high-density aquatic food production is particularly vulnerable to the spread of pests and diseases that are likely to generate both private and external costs via production and quality loss. In addition, there are direct costs of damage control actions, such as vaccines, water treatment, and parasite control, as well as externality costs inflicted upon wild fish fisheries and other nature based activities in the coastal zone. In this chapter, we will discuss some major principles of internal and external environmental issues in aquaculture fish farming. The discussion will commence within the framework of environmental and resource economic analysis, and then applied to issues found in parts of the aquaculture industry globally, in particular to salmon and shrimp production.

13.2 ENVIRONMENTAL ECONOMIC ANALYSIS

Environmental damage occurs when some activities affect the environment in a negative way. In aquaculture, we are usually considering environmental damage associated with non-toxic emissions, such as fish escapees and food residues, but environmental damage can also occur from toxic emissions, such as chemicals and medicine. Nutrients and food residues to waterways can cause significant oxygen reductions for some species living there, diminishing the stock and, in the worst-case scenario, die, even if the discharge itself is not toxic. Food residues from shrimp aquaculture may cause sedimentation in rice fields, thereby negatively affecting rice production. The spread of parasites, such as sea lice (*Lepeophtheirus salmonis*) in salmon production, may spread to wild salmon and cause illness and increased mortality to wild fish, in addition to creating problems within their own and neighbouring aquaculture farms. Salmon lice are found in the Pacific and Atlantic Oceans; they infect Pink salmon, Atlantic salmon, and Chum salmon. In environmental economics, such damages or disadvantages are included in the concept of external effects, that is, unintended impact on well-being (utility) or production possibilities of other actors without affecting the own welfare or profit. From this definition, it follows that a discharge or environmental impact is not necessarily an external effect – in order for this to happen, the welfare of somebody must be affected. Figure 13.1 illustrates this issue of pollution. For example, each of sea lice, chemical substance, food remains, and faeces is a pollutant and the total is called pollution. Thus, the total pollution of one of the pollutants can be quantitatively measured, in Figure 13.1 along the horizontal axis.

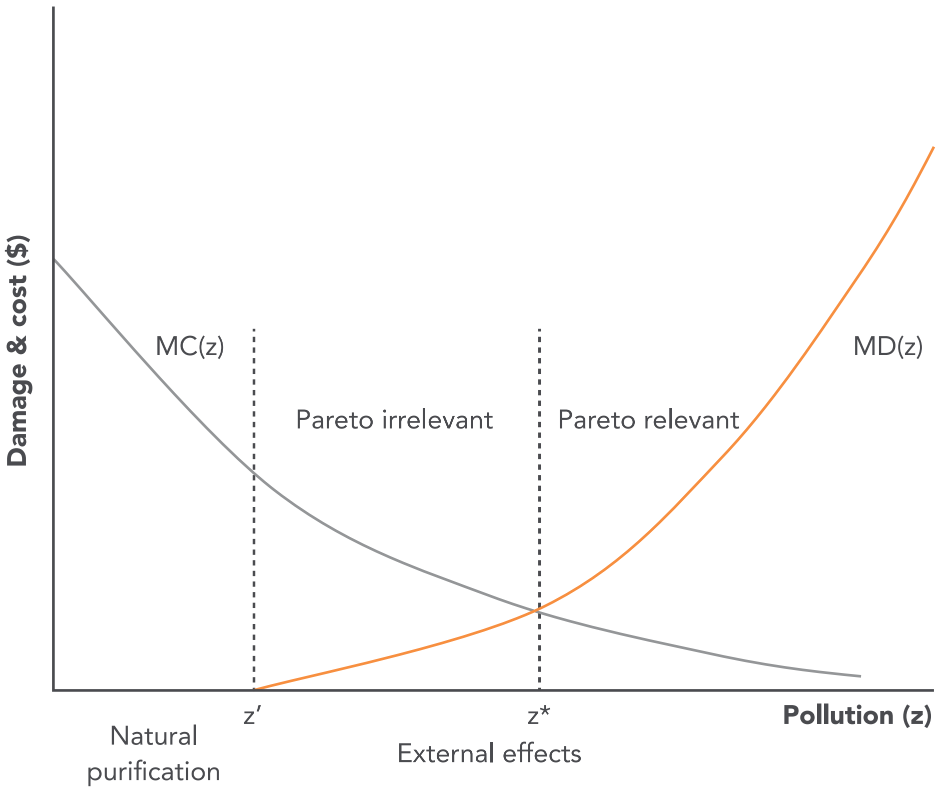


Figure 13.1 Natural purification, pollution, and externalities

Natural recipients may receive limited amounts of pollution without detectable damage or increase in stored (accumulated) discharges. For the release of pollutants z<z', nature can clean it all and there is no harm to others. According to the definition of external effects, therefore, there is no external effect either. For emissions z>z' there is an increasing damage to others per unit pollution, *MD(z)*; thus, there is an external effect. The aquaculture firm releases pollutants to the environment because of the characteristics of its production technology and regular operation, and pollutants from other aquaculture plants may affect it. However, in the long run technological change may take place, in particular in connection with new investments in physical capital. Such investments may also have a bearing on the farm's discharge of pollutants.

Let *MC(z)* be the marginal cost of reducing *z*, for example, by cleaning or reducing production, and let *MD(z)* be the marginal damage cost. Note the slope of *MC(z)* – its more costly to reduce one unit of pollution at low pollution levels than at high levels. For emissions z'≤z<z*, it costs more to reduce emissions than the damage costs, i.e. from a welfare economic perspective there is not a net gain by reducing emissions; the external effects are

so-called pareto-irrelevant (Dahlman, 1979). Only at emissions z>z* is the marginal cost of reducing emissions lower than the marginal damage, and it is beneficial, from a social point of view, to do something about the emissions; i.e. the external effects of the emissions are pareto-relevant for z>z*. The lower limit z^* to the pareto-relevant pollution levels reduces with reduction in the marginal cost of pollution, that is with downward shift in the $MC(z)$ curve. From a theoretical point of view, the regulator may use direct (command and control rules) or indirect (taxes and fees) instruments to correct for externalities and both classes are in use in the aquaculture industries globally. Recall the production function $x=f(q;z,\alpha t)$ in equation (11.1), with z as the negative external effect outside the control of the firm. However, for the first firm to establish an aquaculture plant in an area there are no negative external effects ($z=0$) from other firms, at least not from aquaculture firms, by assumption. However, as more aquaculture plants establish themselves in an area, the pollutants discharged from each of them may negatively affect the production and cost of the others. Thus, also aquaculture firms may have an objective interest in intervention from an outside regulator in their business activities. Pollution from a firm can either be a function of its production, i.e. $z=u(x)$, or of its use of inputs, i.e. $z=v(q)$. Both types are found in aquaculture and will be discussed below.

Our analysis is within a deterministic framework – we have assumed the regulator has full information about emission reduction costs and the damages. Of course, in the real world it is not that simple. First, some negative events for the industry, such as fish diseases, occur occasionally, but it is uncertain when it will happen. Second, externalities develop over time as the industry and society develops. Third, a government agency will not have complete information about all aspects of externalities. Thus, uncertainty and risk should be included in applied analysis to better estimate benefits and costs of government interventions.

Often, waste flow, z, is not the main environmental problem, but the accumulation of waste over time. When it is the accumulation, such as the sedimentation of food residues and faeces on the bottom of the sea or pond, that is the problem, the environmental problem discussed above can be considered like a renewable natural resource problem. The growth equation for this type of problem can then, if we use continuous time, be written as;

$$\frac{dX}{dt} = z(t) - F(X), \tag{13.1}$$

where $X(t)$ now indicates the stock of pollution at time t (again, for example, in tonnes), $z(t)$ gives the flow of pollution, while the cleaning function, reflects nature's ability to "clean up" itself. Note the difference of x (lower case) and X (upper case). In addition, the cleaning function is assumed to be density dependent, and nature's ability to clean up depends therefore on the size of the pollution stock. The accumulated waste materials increase over time **if** the discharge is higher than the natural self-cleaning ability, and decreases in the opposite case. A possible cleaning function (time schedule is omitted) is shown in Figure 13.2, where nature has a positive cleaning capacity up to X_K and no cleaning capacity for higher values of accumulated emissions; so $F(X)>0$ for $0<X<X_K$ and $F(X)=0$ for $X \geq X_K$. For $X=0$, in Figure 13.2, nature has a positive cleaning capacity equal to z^s, which means that as long as the flow of pollutants is less than this level there will be no accumulation of waste. In addition, it is reasonable to assume that the cleaning capacity is increasing for small values of X, reaching a maximum point somewhere in the middle and then decreasing towards the maximum stock of pollution, X_K where nature's cleaning capacity breaks down. However, it could be that X_K is very large with the $F(X)$ curve turning convex and approaching the X-axis asymptotically. Alternatively, nature's cleaning capacity could be at its maximum for X close to zero and then falling gradually towards X_K. Another way of describing this is to move the maximum of the $F(X)$ curve in Figure 13.2 to the left at X very close to zero. The average cleaning capacity $F(X)/X$ is constantly falling because the function is, by assumption, concave.

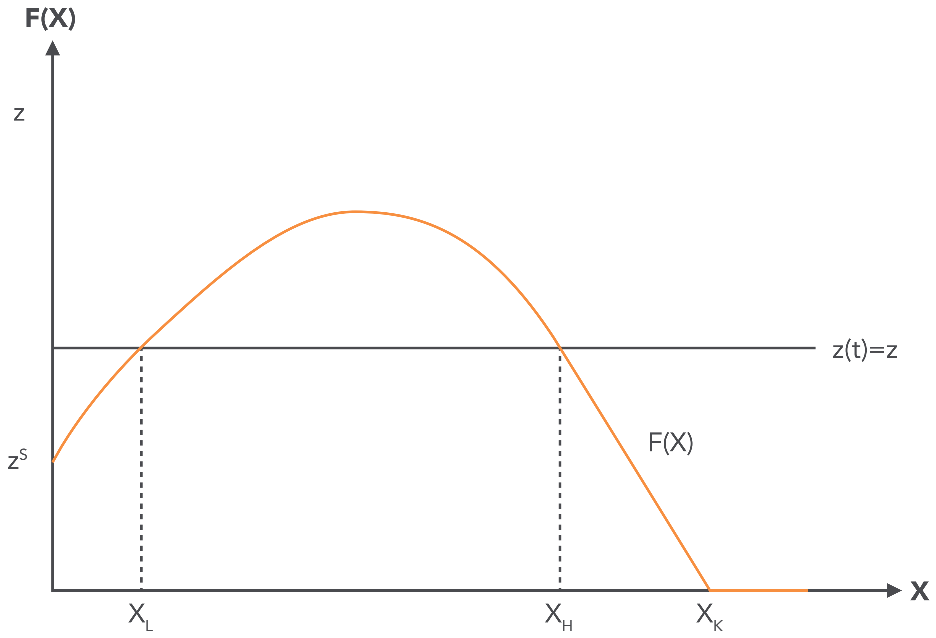


Figure 13.2 Nature's self-cleaning capacity as a function F(X) of accumulated pollution X. z(t)=z indicates a constant flow of emissions

Let us discuss some dynamic pollution issues in relation to Figure 13.2 (the cases of a downward sloping *F(X)* curve and a convex *F(X)* curve for high levels of accumulated pollution are left to the reader). Suppose, for example, that the emission flow is constant over time and equal to *z*. This may correspond to a situation of *z* proportional to a constant aquaculture production so that equation (13.1) can be written as $\frac{dX}{dt} = z - F(X)$. Then, as in the logistic growth model discussed in another chapter, we will again have two equilibria, X_L and X_H. If the initial accumulated emissions are lower than X_L, we see from the growth equation (13.1) that $\frac{dX}{dt} > 0$ and the pollution problem increases. If the initial accumulated emissions are greater than X_L, but less than X_H, the growth equation tells us that we have $\frac{dX}{dt} < 0$ and the accumulated pollution level will decline and approach X_L. If, on the other hand, we start with a value a little higher than X_H, the pollution level will continue to increase, for constant *z*, towards X_K, and even further. Thus, the lowest equilibrium X_L is locally stable, but X_H is unstable. Note the difference in the signs of $\frac{dX}{dt}$ of equation (13.1) below and above *z* in Figure 13.2. If the accumulated emissions have passed X_K, there is no way back; it will still increase whether the pollution flow is constant equal to *z*, as discussed here, or is reduced somewhat. Nature no longer has any self-cleaning ability.

Having discussed, in Figure 13.2, the dynamics of pollution emissions and nature's cleaning capacity, we may now relate this to the damage and cost issues in Figure 13.1, where damage is a function of emission flow. Usually in aquaculture, profit, or welfare, is related to the flow of pollution; greater production and profit means more pollution in the form of effluents from the fish, feed, and the pond or cage. The damage can be a function of the pollution flow (Figure 13.1) or the pollution stock (Figure 13.2). The latter can be illustrated by a function

D(X(t)), where damage increases in stock pollution. This indicates that since emissions from production over time contribute to increased pollution stock, unless cleaned sufficiently, the welfare economic problem should be analysed as an investment problem. In the capture fisheries case, discussed in Chapter 4, production (harvest) contributes to reduction of the fish stock, and the analytic problem is to find the long term optimal fish stock level and the best path from the present to the future. Recalling the analysis, we know that the discount rate plays an important role in the solution. The higher the discount rate the more myopic the fisheries policy should be, with less emphasis on future stock levels. If we did a similar formal analysis of the aquaculture case with pollution stock and damage function based on this stock, we would see a similar solution as in fisheries where the discount rate plays a role in the optimal solution. However, the optimal long run accumulated pollution, X^*, will depend positively on the discount rate, δ; $dX^*(\delta)/d\delta > 0$, which is the opposite of what we have for the optimal fish stock (Chapter 4). The explanation is that a high discount rate reflects a preference for present net benefits without too much attention to future environmental costs.

The similarities between z' in Figure 13.1 and z^s in Figure 13.2 require a comment. The former has two meanings; first, it is the upper limit to how much of the emissions nature can clean without accumulation of pollution, and in this respect it corresponds to z^s in

Figure 13.2; second, *z'* is the lower limit for a positive marginal damage, and in this respect it represents society's valuation of emissions. It could be that this lower limit was smaller than *z'*, which would be the case if the social valuation of emissions were negative even for low levels of emissions. The marginal damage function *MD(z)* may represent elements of non-market valuation and not just market and objective scientific valuation. It could of course also be that the lower limit for a positive marginal damage in Figure 13.1 was higher than *z'*, reflecting society's attitude to external effects. Recall the definition of external effects, that is, "unintended impact on well-being (utility) or production possibilities of other actors without affecting the own welfare or profit." Considering all the pollution observed in most countries it is tempting to say that societies more often than not accept a level of pollution above nature's ability to clean. Not just in relation to aquaculture, but also to several other industries.

13.3 ENVIRONMENTAL ISSUES IN SALMON PRODUCTION

The main five environmental and externality challenges in Atlantic salmon aquaculture are

1) escape of fish that may threaten and weaken wild salmon in the spawning rivers;
2) parasites, in particular sea lice, that may affect wild salmon as well as harm the health and quality of the farmed fish;
3) feed remains and faeces that may accumulate on the sea bottom under and nearby the cages;
4) fish diseases, that may spread to wild fish and neighbouring farms, as well as causing increased mortality, fish health problems, and lower quality of the farmed fish; and
5) sea space use, including both surface area, volume and bottom, at the expense of other industries and recreational purposes.

An effective way of restricting aquaculture emissions and other negative externalities is to limit the size of the industry within a geographical area, and slow down the growth. The salmon example mentioned at the outset of this chapter demonstrates that something went wrong in Chile, the world's second largest producer of Atlantic salmon. For a discussion of what and why see e.g. Asche et al. (2009) and Iizuka and Katz (2017). In Norway, limited entry through licensing has been the main policy instrument from the early 1970s, since the preliminary Aquaculture Law enacted in 1973. All fish farms need a licence to enter and operate in the industry. The present Aquaculture Act entered into force in January 2016, and is followed up by more detailed rules and regulations. To protect the local environment from adverse effects of emissions, regional governmental offices have a strong say in the location of farms. In general, they are now located further out in the fjords where sea currents in a natural and inexpensive way help to reduce local pollution. Farm size is, since 2005, limited by maximum allowable biomass (MAB). A standard license for salmon, trout, and rainbow trout is 780 tonnes of live biomass, with the exception of the northern most county of Troms and Finnmark, where a license is up to 945 tonnes. When the first regulations through licensing took place in the 1970s a limit on cage size was the main instrument to control development. First, volume was restricted to 3000 m^3 per license, later expanded three times to 12,000 m^3 in 1989 and this lasted until 2005. In addition to cage size limitations, feed quotas were introduced in 1996 as production regulatory measures in the industry. This required reporting of production and feed consumption data. The reporting scheme was continued, but adjusted to provide the best possible information about the biomass situation in the farms. All in all, throughout the history of salmon aquaculture in Norway licenses used to include both technical regulations and input controls with the objective of reducing environmental externalities such as fish escape, parasites, and sludge and nutrient salt emissions (Aarset and Jakobsen, 2009; Liu et al., 2011; Hersoug and Mikkelsen, 2018). Aquaculture licenses are transferable between firms, but there is a limit (40 percent) to how much one firm may acquire. A license allows the establishment and operation of a farm, provided an approved location is available, but this is not a real property right for a given space in the coastal zone. The location is allowed as long the license is used for actual operation within the legal limits of laws and regulations. Nevertheless, a license and a good location can be worth 60-70 million NOK (USD 8–9 million) (B. Hersoug, UiT-the Arctic University of Norway, personal communication).

Norway had its maximum number of salmon escapees in 2006 with 921 thousand fish, after a gradual increase in the preceding years. Later the numbers went down, reaching 126 and 10 thousand individuals in 2016 and 2017, respectively. These are officially reported numbers, but regulatory agencies state that the real number may be somewhat higher. With a coastline of about 2500 km (more than 100,000 km when including inlets and islands) and more than 400 rivers with spawning wild salmon, there are many reports of escaped farmed salmon in the rivers. The fear is the occurrence of interbreeding between farmed and wild Atlantic salmon (*Salmo salar*), deteriorating the genetic pool of the wild salmon, as well as weakening of the hatching of wild juveniles from occupation of first class spawning spots by escaped salmon (McGinnity et al., 2003).

There are several causes of escapes, including rampage and attack by predators (seals and other), collision between the cage components and service boats, mistakes in handling net and cage, failure of equipment or contact between components, and contact with bottom and chains. To reduce and minimize escape numbers, rules and regulations for both equipment and operation were developed, including stating the responsibility of farms to contribute to the re-catch of escaped fish and to pay damage compensation. Operational managers can also be fined, and even imprisoned for serious misconduct. Relating this to Figure 13.1, the damage of escaped farmed salmon is particularly in regard to the wild stocks migrating to rivers to spawn. Governmental target points are used, including the number of farms and biomass in an area and the minimum distance to salmon rivers and slaughter plants. For a discussion of the relationship between aquaculture and wild salmon in Norway, see Liu et al. (2011).

Of the salmon parasites, sea lice is the most common one, causing both production problems and externalities. Management of modern aquaculture is to a great extent based on and dependent on scientific knowledge. However, the scientific evidences are not always clear, as an example from Canada demonstrates. A study in British Columbia linked the spread of sea lice (*Lepeophtheirus salmonis*), from river salmon farms to wild pink salmon in the same river, and concluded that some wild pink salmon populations were "on a trajectory toward rapid local extinction." (Krkošek et al., 2007). However, another group of scientists expresses another view, referring to Krkošek et al. (2007). "Their prediction is inconsistent with observed pink salmon returns and overstates the risks from sea lice and salmon farming." (Riddel et al., 2008). The 2007 paper was corrected somewhat by the authors in 2008, but without changing the main conclusions of the report.

There are currently several means in use to reduce the sea lice problem occurring in the aquaculture salmon countries. Both Norwegian and Scottish farms have introduced wild and farmed small sized fish preying on sea lice with the purpose of cleaning salmon of ectoparasites. Globally, salmon production fell approximately 9% in 2015, mainly due to acute outbreaks of sea lice in Scotland and Norway. The development of resistance against drugs most commonly used to treat salmon lice is a serious concern for both wild and farmed fish. Lasers, physical cleaning, cleaning fish, and chemical baths are used to reduce lice infections, adding to the production cost. As of 2017, nearly half of Scotland's salmon farms are infested with salmon lice. The problem is growing worldwide, with lice being far more resistant than the industry thought, according to Wikipedia (2018). For recent and thorough analyses of lice in the Norwegian salmon aquaculture industry, see Torrison et al. (2013); Abolofia et al. (2017); and Iversen et al. (2017).

Lice protection and management in Norway

Any follow-up and treatment against lice requires that you have a good overview of the lice situation. The lice situation is therefore monitored continuously, partly as a result of statutory requirements, but some breeders count more often to get the best control. The number of salmon lice is counted at least every 7 days at temperatures equal to or above 4 °C, and at least every 14 days at temperatures below 4 °C. The industry has previously carried out voluntary coordinated cleaning in the spring – however, in the Lice Regulations this measure has been replaced with a lower average lice limit per fish in the spring. This has been considered particularly important for shielding spring migrant young salmon (smolt) from the river breeding ground to the ocean. The Lice regulation states the following about limit values for lice:

- In the county North Trøndelag and south, from the Monday of week 16 through to Sunday in week 21, a maximum of 0.2 adult female salmon lice on average per fish is allowed in the aquaculture plant. From Monday of week 22 through to the Sunday of week 15 the corresponding limit is 0.5 adult female salmon lice.
- In Nordland, Troms, and Finnmark, from including Monday of week 21 through Sunday of week 26, a maximum of 0.2 adult female salmon lice on average per fish is allowed in the aquaculture plant. From Monday of week 27 through to Sunday in week 20, the corresponding limit is 0.5 adult female salmon lice.

The Lice Regulations also states that measures must be taken to ensure that the amount of salmon lice does not exceed the limits. If necessary, fish decommissioning may be requested by the regulatory agency.

(Translated from Iversen et al. (2017) by the author)

Salmon lice has severe effects on the farmers' fish if appearing in high numbers. Therefore, farmers have an economic interest of their own to limit the lice population on their salmon. It is a question of balancing marginal revenue and marginal cost of lice removal, accepting that it is not possible to completely avoid this damaging parasite. In addition to the private benefits and costs, society adds social elements; in this case to the cost side. Analysis, as in Figure 13.1, may help in understanding the main issues involved, recalling that the marginal cost of damage includes both private and social elements. Whether it was a thorough benefit-cost analysis that lead to the Norwegian rules discussed in Box 13.1, or a back of the envelope thinking, is not known to the author. It is a rather strict regime that requires a lot from the farmers as well as from the government agencies managing the system. A slight change in Figure 13.2, let $z^s=0$ for $X=0$, may also contribute to the understanding of the lice problem and its solution. With X as the stock and $F(X)$ as the growth of lice, which is similar to the fish growth models, we now have that private damage for the farmer mainly depends on X and social damage mainly on growth and dispersal from $F(X)$. A large X contributes to fish of inferior quality and increased mortality; thus, for the farmer we may express the damage to their own fish stock as $D(X)$. The externality is mainly connected to the spread of lice to the environment outside the farm, including to wild salmon; this damage $D(z)$ depends on the lice production, $z(t)$ and on how much lice is "harvested" or killed per unit of time, k. The dynamics of the problem is $z(t)=F(X)-k$, and social optimum requires balancing benefits and costs. Targets may be related to z or X, knowing they are interconnected. The Norwegian method, described in Box 13.1, is indirectly based on X, since lice per fish and a known number of fish in the floating cage gives the total number of female lice. Note that targets vary geographically and seasonally, adapted to the expected damage. The killing of lice, equal to k in the dynamic equation, can be done in several ways, and it is left to the farmer to choose a cost-effective method that pays attention to fish welfare, health, and quality.

The cost of Norwegian salmon farming now continues to grow. Average production costs for salmon fell steadily from the start of the industry up to 2005. From 2005 to 2016, the cost per kg produced have approximately doubled in nominal values. Even adjusting for inflation, the cost increase is just over 60 per cent, according to a recent report (Iversen et al., 2017). Increased feed cost and increased cost for monitoring, prevention, and treatment of lice are the most important explanations for the total cost increase. Salmon lice prevention cost increased per kg produced from about one NOK in 2011 to 4.25 NOK (0.50 USD) in 2016. The total cleaning costs are around 5 billion NOK (595 million USD) a year (in 2016), but the growth in lice cleaning costs has leveled. Prevention of lice by drug-free treatments increase, and with a strong reduction in bath treatments, it may seem that lice costs are reduced by 2017 (Iversen et al., 2017). The Norwegian veterinary institute (NVI) and others are researching to develop a vaccine against sea lice. If successful, based on the discussion above, this may save significant costs for the industry.

According to NVI about 53 million salmon died in the floating cages in 2017, and with an average slaughter weight of 4.5 kg at today's market price, this amounts to more than 13 billion NOK (1.6 billion USD) gross. There are significant differences in mortality between regions, highest in the South West with more than twenty per cent and lowest in the North with less than half of this. There is no comprehensive analysis explaining the exact reasons behind this mortality, but sea lice seem to be a key problem. Some individuals weakened by the parasite die from wounds, in particular recently released small juveniles, but many more die through the lice cleaning processes (Veterinærinstituttet, 2018).

Floating cages in salmon production release feed remains and faeces to the sea, creating sludge and nutrient salt emissions, and this may have external effects on neighbouring farms and people's recreational use of the coastal area. Technological solutions with closed or semi-closed cage culture, also land based, exist, but are considered too costly for the salmon industry and are hardly used. However, operating technology to monitor fish appetite and feed consumption in the floating cages has been developed and put into use, both to reduce waste discharges and to save on feed costs. Traditionally, in the global aquaculture industry, the human eye and the experience of the farm operator contribute to keeping feed use and discharges at acceptable levels. Overall, it is costly for the farm to reduce the discharge of pollutants, and we should not expect this to happen voluntary in a market economy, unless the farm saves in costs, e.g. by reducing the use of feed. However, social cost and benefit may be different from private cost and benefit and a social planner may wish to intervene in the market. A farm can, to some extent, reduce discharges of feed remains and faeces, but the incentive to do so is weak, unless required by governmental regulation. The system with feed quotas introduced in 1996, discussed above, was aimed to dampen production growth and emissions. However, due to other weaknesses this was abolished in 2004, and farm size and MAB restrictions took over as the main regulatory means to curb growth and emissions. In the Norwegian salmon industry recent technological developments, such as underwater lights and surveillance cameras to monitor fish appetite and behaviour, contribute to reduced feed waste and cost, as well as to a better underwater environment.

In the 1980s, fish disease lead to increased mortality and hampered industry growth. The immediate answer was to use more and more antibiotics to curb disease outbreak (Figure 13.3). However, fear of short and long term environmental damages and market reactions from consumers lead to the development of vaccines against the most common diseases. Can we explain the use of salmon vaccines in light of the theory displayed in Figures 13.1 and 13.2? Let us try; If some fish in a cage get sick it is very likely that others will also be infected. In the worst case, disease can be lethal, creating significant loss to the farmer. The pathogens can easily spread through the water to other nearby cages the owner may have, worsening his economic situation. Still, this is not an externality as discussed above. It is all the problem of one aquaculture plant, to be managed within the firm. However, in all modern salmon producing countries the floating cages of the neighbouring farm are not far away.

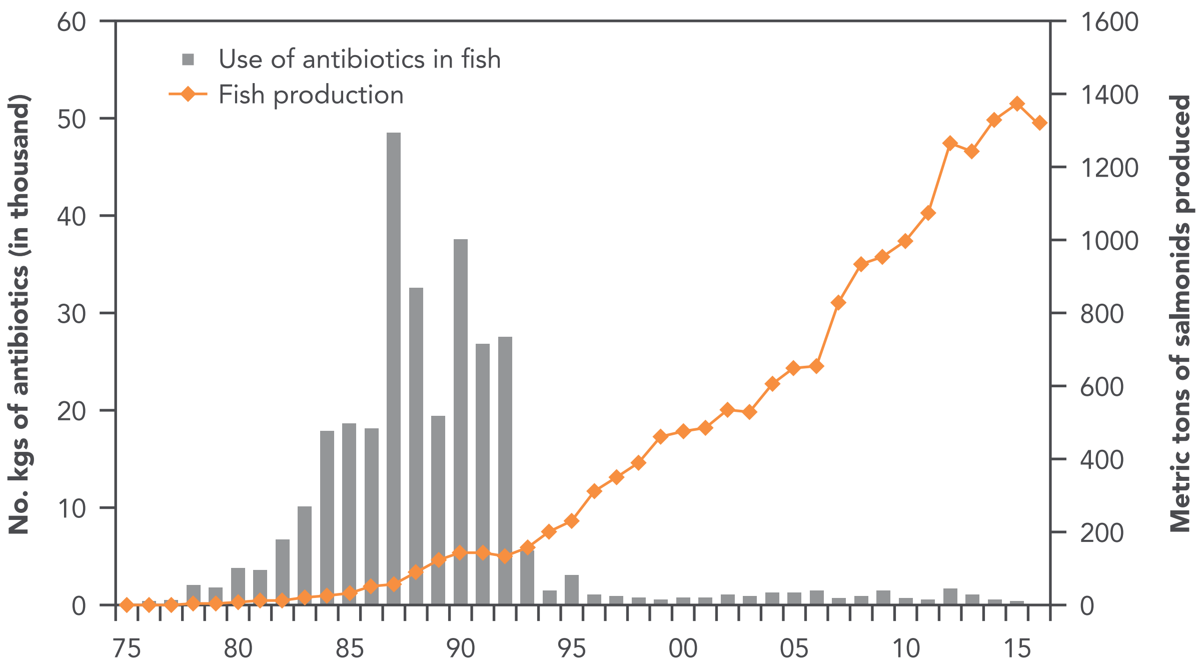


Figure 13.3 Antibiotics used in Norwegian aquaculture and the production of salmonids, 1975–2016.
Source: Norwegian Veterinary Institute

In the wild, diseases and parasites are normally at low levels, and kept in check by natural predation on weakened individuals. In crowded ponds and floating cages, they can become epidemics. In some cases, this requires the eradication of the entire fish stock of any farm if an outbreak of disease is confirmed. Management strategies include the development and use of vaccines and improving genetic resistance to diseases. Such efforts do not come for free. As an example, all juvenile salmon (smolt[34] – ready to go to sea) released into sea cages in Norway must be vaccinated against three diseases (furunculosis, vibriosis, and cold-water vibriosis). In addition, vaccination against pancreas disease (PD) in Mid- and South-Norway is statutory, as part of a governmental strategy to control the spread of this disease[35]. Vaccination is generally done by injection with polyvalent vaccines containing all, or most, of the disease components in one dose. The average vaccination cost is 1.32 NOK (USD 0.16) per juvenile fish (in 2016). All types of vaccines are included in this average cost, amounting to 13.1% of the total production cost per smolt. In addition, for some firms there may be some labour costs related to the proper injection of the vaccine that are not included.

Fish diseases are not of the same severity in all parts of the country; generally, further north with the colder climate and a lower density of fish farms the problems are milder. Thus, in 2016 the vaccine cost per smolt in the two northernmost counties, including Tromsø, was 1.16 NOK, against 1.40 NOK in the South-West, including Bergen. Annually, more than 400 million fish, hatched and raised in fresh water tanks, are released into sea cages for them to grow out. In addition to contributing to an amazing improvement in fish health and reduced mortality in the grow out phase, fish vaccines have nearly eliminated the need for antibiotics in the salmon industry (Figure 13.3).

Disease and mortality challenges in the 1980s could not have been solved without vaccination that proved to be a very cost-effective way of reducing fish mortality (Lilletun, 1989). The overall aim of vaccination in aquaculture is to increase economic output by reducing losses due to disease, including expenses for medication and other costs, weighed up against the costs of vaccination (Lilletun, 2014). In addition, antibiotics in fish would probably have had market implications and made it difficult to sell about 1.2 million tonnes of salmon annually, in 2017. Thus, vaccines have had two important economic effects, reducing the average production cost and contributing to food safety and consumer preferences of salmon products (Fiskeridirektoratet, 2017).

Available productive areas in the coastal zone is one of Norway's most important competitive advantages as a farming nation. The coastal area used to be a surplus resource without the need for an overall management plan of the use. With the growth of the aquaculture industry, and to some extent also other coastal economic activities, this is now a retired stage. Access to good farm space is a scarcity factor for sustainable development of the industry (Hersoug and Johnsen, 2012). A Ministry appointed expert committee for efficient and sustainable land use in the aquaculture industry in 2011 came forward with proposals for a new overall area structure (Arealutvalget, 2011). The objective was to help the aquaculture industry exploit the coastal zone on a sustainable and efficient basis, with less environmental impact and risk of spread of infection. This should also contribute to a balanced coexistence with other interests in the coastal zone. The expert committee emphasized three main challenges; escape, salmon lice, and loss in production, whose solutions depend on good overall management of the coastal zone. Remedies to solve these problems include the division of the coast into separate production areas and designated zones monitored through indicators and action rules. The industry in each production area is given a stronger direct social responsibility to solve common challenges. This has been followed up by the Government and included in the numerous laws and regulations concerning, directly or indirectly, the aquaculture industry[36].

A few years ago, several reports discussed the possibility of a huge increase in the Norwegian aquaculture production (for a review, see the White paper to the Parliament, Meld. St. 22 (2012–2013) on "the world's premier seafood nation"). One key research and development report discussed in the white paper suggested the possibility of a five-fold increase in the Norwegian aquaculture production by 2050. Then we may ask, is there enough space for such a huge expansion? From a macro point of view the answer seem to be affirmative. The proper farm cages do not occupy that much space. However, at the local level, there are some objections. First, it is recommended a minimum distance of 2 km, preferably 5 km, between any two farms. Second, municipalities and counties have a special responsibility to produce and roll over coastal zone plans and to develop a wider regional and intermunicipal cooperation on such plans. Licenses for aquaculture production are granted at the governmental level, but space for farms are the main responsibility of municipalities, coordinated at the county level[37]. Third, many municipalities have expressed frustrations about receiving the emissions locally, whereas profit and resource rent are channelled to the companies' headquarters in the bigger cities. To help communities get more in return for allowing their sea space to be used by the aquaculture industry, recent allocation of licenses have been through auctions and a share of the proceeds have been granted to the municipalities (Hersoug and Mikkelsen, 2018). Local communities are now also allowed to include the aquaculture farms in their property tax regimes, but the proper fish capital is exempted. Maybe the expected great battle for space, if the Norwegian salmon industry is going to increase its production five-fold by 2050, will be peacefully solved by such tax and license fee sharing rules? However, the environmental issues related to escape, sea lice, and other emissions still remain to be solved, at least partially.

13.4 ENVIRONMENTAL ISSUES IN SHRIMP FARMING

Among the most important environmental issues discussed in aquaculture shrimp production are

1) Mangrove forest reduction
2) Space requirements
3) Salinization/intrusion of sea water
4) Sedimentation
5) Disease

Asian countries are leading the world in aquaculture shrimp production, amounting to billions of US dollar annually. It has been a success in several countries, such as India, Indonesia, Thailand, and Vietnam, as well as Ecuador (see chapter 11). Globally, shrimp now ranks second in value terms (Table 12.2) despite some serious setbacks when nature strikes back.

In some cases, the mangrove forests, important providers of ecosystem services, have been demolished to make room for more profitable shrimp production. Environmental and resource economists, as well as natural scientists, have long ago investigated the mangrove reduction problem, evaluating the benefits and costs of such human activities (Barbier and Strand, 1998; Naylor et al., 2000). One of the most important ecosystem services provided by mangrove forests is as a breeding and nursery habitat for wild fish, including shrimp and crab, and traditionally this is considered economically valuable. On the other hand, if fisheries are open access, conventional bioeconomic analysis does not give much credit on the benefit side of keeping the mangrove unspoiled. However, as discussed in previous chapters, we know that intra-marginal rent and consumer surplus, as well as local employment and ecosystem services, may contribute positively to welfare even in open access fisheries. Of course, this is even better if it is a well-managed fishery depending on the mangrove nursing of its juvenile fish. This is particularly important if the mangrove forest is essential, with no alternatives, for nature to replenish wild juvenile fish in a given area.

Some studies of fishery-mangrove linkages conclude in favour of keeping the aquatic forest instead of removing it for aquaculture or tourist development purposes. "Mangroves are disappearing rapidly worldwide despite their well-documented biodiversity and the ecosystem services they provide. Failure to link ecological processes and their societal benefits has favored highly destructive aquaculture and tourism developments that threaten mangroves and result in costly "externalities". The destruction of mangroves has a strong economic impact on local fishing communities and on food production in the region" (Aburto-Oropeza et al., 2008). The fact that mangroves are disappearing and aquaculture plants are established in many of these areas is a strong indication that this is a profitable change for private businesses. Whether this is also the case from a welfare economic point of view remains to be investigated case by case.

If, in a given area, there are two choices, either "keeping the whole mangrove forest as is" or "destroying it all to establish a shrimp farm" we are faced with two independent investment projects that can be analysed with environmental present value methods. If, on the other hand, the size of both the shrimp farm and the mangrove is flexible, the problem can be analysed in a similar way as in Figure 13.1. Pollution, measured horizontally, in the form of effluents from the farm, depends on the shrimp quantity produced. Increasing pollution from aquaculture means fewer ecosystem services from the mangroves and the marginal damage is increasing progressively. The horizontal constant marginal cost is higher than the marginal damage for a low quantity of pollution, and of shrimp production. However, as this expands the marginal damage will be higher and higher until it equals the marginal cost, for the welfare economic optimal quantity. Thus, within such an analytic framework it may well be an internal optimum solution with some natural mangrove forest and some shrimp production (or other industrial activities), and not a corner solution with either the entire virgin mangrove or no mangrove forest. This is the principle picture, which is useful for organising our thinking, but the common problem of damage measurement can be difficult to solve.

Coastal areas suitable for shrimp farming is scarce in most countries. Low-lying areas in South and South-east Asia, for example, are densely populated and land generally already occupied by agriculture, settlements in villages and cities, industries, and infrastructure. When shrimp farming became profitable, in particular as high-priced goods for the world market, it was often developed as extensive production in mangrove forests and other marginal sea-land areas not used for traditional agriculture or other direct human activities. Such extensive production meant enclosure of shrimp in a relatively secure system under conditions in which they can grow. Exclusion of predators and control of competitors are necessary first steps in aquaculture. For further expansion on land, but close to the sea, it had to compete its way with the other human activities. In some cases, this could be done in joint utilisation of the land. For example, in the coastal areas of the Mekong Delta, many farmers have adopted shrimp farming in the dry season, when severe saline intrusion makes it impossible to grow rice. These extensive and semi-intensive culture methods include integrated shrimp-rice, and also shrimp monoculture systems. Such adaptation of shrimp farming has raised incomes for several farmers in the region, but in the long run some experience that nature strikes back with environmental problems. Going back to the discussion of Figure 13.2 it is the accumulation of waste, such as salty fields and sedimentation of the shrimp ponds that could reduce the productivity and increase cost of rice production. This could also spread to neighbouring rice monoculture fields.

Increasing the degree of specialisation and control of the production process leads from extensive farming to semi-intensive, with an enrichment of the food supply, and further to intensive shrimp production, with the provision of all nutritional requirements. The latter also implies increasing the density of shrimp, and greater use and control of inputs. Higher density means greater emission of waste products and increased potential for the spread of pathogens internally and between farms. Digging and construction of separate ponds along riverbanks for intensive farming, could in some cases take place on cheap land that is proved less suitable for agriculture, for example due to salt-water intrusion. In other cases, shrimp farms had to compete for land against agriculture and other human activities already in place.

Competition for space was not always on equal, fair, and legal footing, as this quotation from Primavera (1997) demonstrates "grave socio-economic consequences – including conversion, expropriation, and privatization of mangroves and other lands; salinization of water and soil; decline in food security; marginalization of coastal communities, unemployment and urban migration; and social conflicts – have followed in the wake of shrimp farm development in the Philippines and other tropical countries." In the literature there are numerous papers quoting this paper, both case studies and general discussions by natural scientists, technologists and social scientists, and the investigative student may want to explore further such issues (you may use Google scholar https://scholar.google.com/).

From a business economic perspective shrimp disease has been the hardest problem to cope with in the otherwise successful aquaculture production. Environmental issues in shrimp aquaculture are related to both flow and stock issues; this is also so for economically devastating diseases. Diseases may cause sudden changes in shrimp production, such as that of Thailand discussed at the outset of this chapter. In most countries, production has gone from extensive to semi-intensive and intensive production methods (recall chapter 11 for a discussion on Vietnam). The experts seem to agree that the risk of diseases increases with pond densities in an area and with stocking density within each pond (see Kautsky et al., 2000), and later papers quoting this). In other cases, integrated shrimp-rice production, profitable at the outset, gradually erodes the advantage of joint production. Through shrimp culture in the dry season (pumped water) and rice in the rainy season, feed, chemicals, and high stocking densities may place stress on the soil for rice production. Farmers do not always have full information about future disadvantages for the rice fields of the joint production. Biological production in a natural environment is risky, and this is an important reason why intensive shrimp production in specialised ponds has expanded.

There is a huge literature on shrimp diseases, and some suggestions on what to do. Farmers are primarily concerned with how to quickly diagnose a disease outbreak in the pond and to treat the shrimps with chemicals and medicine to improve the situation. Ecologically inclined scientists and industry managers are more concerned about the long run ecological, economic, and social sustainability of the farming. Of the common problems contributing to diseases are the following ten, often mentioned:

- High stocking density in the pond
- High pond densities within an area

- Shortage of clean water
- Insufficient waste removal from the ponds
- Fluctuation in abiotic factors like oxygen, salinity, and temperature
- Sedimentation accumulating heavy metals and other bad substances
- Hatchery reared larvae that increase genetic uniformity
- Global and regional transport of seed larvae and brood stock may transfer diseases
- External pesticides and pollutants, including from agriculture
- New viral pathogens pop up and take the industry and scientists by surprise

(see Kautsky et al., 2000; Flegel, 2006).

For small quantities of aquaculture production locally, there is hardly any environmental damage and disease is to cope with. However, intensive stocking of shrimp and transboundary transfer of biological materials have proved devastating in some cases. Numerous diseases are reported, mainly virus related, but also bacterial. In Asia, starting in Thailand, tiger shrimp (*Penaeus monodon*), was the dominating shrimp, but after the turn of the millennium this changed and white leg shrimp (*Litopenaeus vannamei*) soon became the dominant species. Different growth characteristics, reducing the production cycle, were the main reasons for this change (recall chapter 12). In addition, the monodon shrimp had developed more and more diseases, whereas some of these were not transferred to the vannamei.[38] Treatment of shrimp diseases, by chemicals and medicine, can be a significant cost to the farmers; in the South Central Vietnam in 2014 chemicals, including antibiotics, amounted to approximately 2 and 14 per cent of total operating cost for extensive and intensive production, respectively (Thanh Thuy Pham, PhD, Post Doc, UiT – The Arctic University of Norway, personal communication.)

Farmers of course do something to minimize the risk of getting disease in their shrimp stock, including in designing the farm; for example, with fresh water flowing in at one end and wastewater going out downstream. However, often the downstream wastewater, mixed in the river flow, is the freshwater of the next farm. Pathogens spread this way, though in a dampened way. For the grow out phase it is important for the farmers to have methods for quick diagnostics, and easy to use test kits have been developed for some of the diseases, whereas other tests are confined to the laboratories (Flegel, 2006; Thitamadee et al., 2016).

What about vaccines against all the shrimp diseases? Of course, shrimp cannot be vaccinated the way salmon are, by injections, which would be both difficult and extremely costly. However, for some of the disease immune responses can be provoked in other ways, and research is taking place to improve and expand the methods to more and more diseases. Molecular biology is used for a better understanding of shrimp and disease biology and the interaction between the two. "The combined result of all of these developments has been a continuing increase in production of cultivated shrimp. In the future, it is expected that the world shrimp industry will have ready access to a variety of domesticated, genetically improved shrimp stocks free of all significant pathogens" (Flegel et al., 2008).

13.5 CONCLUDING REMARKS

We have seen above for the case of Atlantic salmon aquaculture in Norway that public management has been successful in the sense that there have never been significant setbacks in the growth of production, like in Chile. However, in the last three to four years production growth may have come to a halt. The management system is comprehensive, with 10 laws, 55 regulations and 900 paragraphs the industry should obey. Specific public agencies, in particular one major, in addition to the regular law enforcement system, monitor the private industry. For many firms and people around the globe this may sound bureaucratic and unmanageable. Nevertheless, it has worked in the Norwegian context where good institutions and little corruption dominates (Nadarajah and Flaaten, 2017). The author is not knowledgeable enough about the management systems in the major shrimp aquaculture countries to discuss it in this chapter, but would rather leave it to the readers to do it on a case-by-case basis.

For both shrimp and salmon, diseases – including sea lice – have kept a lid on the growth rates of these industries. Despite significant effort to develop methods to rid the ecosystems of pathogens, there is still a long way to go. A lot has been achieved already, and more disease problems will be solved, fully or partly, in the future. However, this author thinks it is too good to be true that all disease problems in aquaculture can be solved. Dense stocking of animals in water is prone to catching old and new diseases, and zero mortality will hardly be achieved. The question is rather, can disease protection costs and mortality be kept so low that the grow out and revenues from this still makes the aquaculture firms profitable in the long run. In addition, for society it is a question if the economic surplus is large enough to defend also the externality costs inflicted on other industries, wild fish, and people inhabiting the coastal zone. Whether the aquaculture firms should be asked to pay taxes or fees to compensate for the externalities, or the surpluses should be left as super-profit within the industry, is another question. Most economists would say that the polluter should pay for the negative externalities. But what if there still is a super profit in the industry? What do you, dear reader, think?

14 PLANT AND INDUSTRY MANAGEMENT

14.1 THE BASIC PROBLEM

Aquaculture is the cultivating of freshwater and saltwater populations under controlled conditions, and can be contrasted with capture fisheries. However, in some ways aquaculture may be compared to that of optimal management of wild fish under known conditions. The basic biological characteristics of fish is much the same – fish is "recruited" to the fish farm as fingerlings (juveniles), they grow, some may die from predation or diseases, and the important questions for the farmer are: How much feed should be given to the fish? When to harvest? What size or age of fish at harvest will maximize the farm profit? This resembles how we analyse the optimal harvest of a single cohort in chapter 8. There are, however, some important differences between aquaculture and wild fish industries: Recruits are costly whether they are purchased in the market or produced within the firm. To grow the fish needs feed and this is costly. The natural mortality from predators is easier to control in captivity than in the wild. Densely stocking of fish may cause diseases that affect growth, mortality and/or the quality of the fish. Harvest is easier to control, both with respect to timing and technology, to reach a beneficial market price. We shall discuss all these issues more in detail within a theoretical framework.

If fish could be recruited costless to the farm and kept to grow without feed costs – a dream scenario for fish farmers – the main issue would be to choose the age or size of harvest. In fact, this resembles fish in some agricultural rice farms when herbivore juveniles come with the flood water and find their own natural food. It also resembles a basic problem in forestry – at what age should trees be cut down and brought to the market? Both fish in captivity and trees are the capital of the aquaculture farmer and the forest owner, respectively. How should they manage the natural capital to maximize their wealth? Fish weight increases with time (age), for example as in Figure 14.1 (for other examples see Chapter 8). This is a stylized Atlantic salmon (*Salmo salar*), reaching about 15 kg in 1000 days and with decreasing relative growth throughout its lifespan (see Annex D for the growth equation and parameters). To simplify the discussion the typical seasonal and temperature affected pattern of salmon growth is not included (Jobling, 2003). In the analysis that follows, in particular the relative growth of fish is important for the optimal age of harvest.

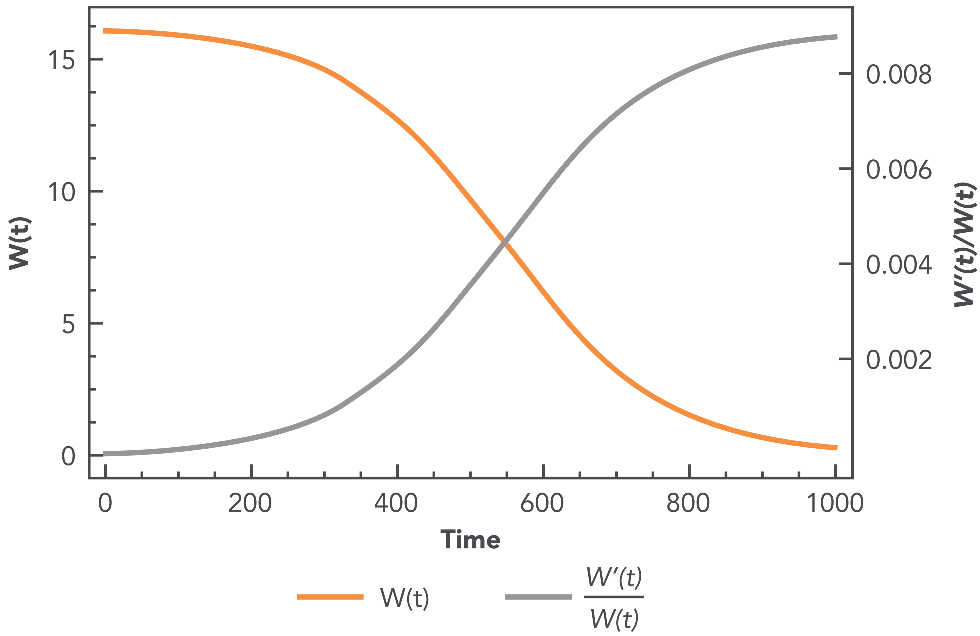


Figure 14.1 Fish weight (lhs) and relative growth (rhs) as functions of age (in days).

Let us start with a fish farm with a given capacity, be it earthen ponds or floating cages in the sea. Fish recruits released into the cage, to use this term throughout, grow larger and the first question is – when to harvest with the objective of maximizing the owner's wealth? We will come back to the costs of recruits, feed and slaughter, but for now we disregard these costs to highlight discounting and wealth maximisation. Let $V(t)$ be the value of fish at time t and δ the interest rate, or opportunity cost of capital. The problem is to $MAX_t\, \Pi(t) = V(t)e^{-\delta t}$, using continuous time. Recalling the investment analysis in chapter 4 we derive the first order (FOC) condition for the maximum, also called the simple Fisher condition $\frac{V'(t)}{V(t)} = \delta$. The relative value growth is, by assumption, declining in this analysis, and this corresponds well to actual cases of biological growth, as demonstrated in Figures 8.1–8.4 (just add a constant price per kg fish). The fish farmer should let the fish capital grow as long as its relative growth is greater than the discount rate, then harvest when the relative value growth equals the opportunity cost of capital. Compare this to the discussion in chapter 4 where we concluded that a positive discount rate implies harvesting at a lower stock level than with zero discounting.

The value of fish at time t depends on the market price, average weight and number of fish, p(w), w(t) and N(t), respectively. Initially, we assume the price (e.g. USD per kg) depends on the size of fish, which is often the case in actual markets, but it could have been constant across size groups. When R recruits are released at time zero they will start growing, but some will die while ageing, even in aquaculture (see chapter 13), and at time t there are N(t) left. Thus, the biomass at time t is $B(t) = Re^{-Mt}w(t)$, when the instantaneous mortality rate is M. Further,

$MAX_t\, \Pi(t) = V(t)e^{-\delta t} = p(w)w(t)Re^{-Mt}e^{-\delta t}$. Using the symbols $p' = \frac{dp(w)}{dw}$ and $w' = dw(t)/dt$, wealth maximum now requires the following the reader should do the calculations and check that this is correct)

$$p'(w)w'(t)w(t) + p(w)w'(t) = [\delta + M]p(w)w(t). \tag{14.1}$$

The left hand side (lhs) of (14.1) is the marginal revenue with respect to time, and this consists of two terms. The first term is the marginal price increase and the second is the marginal weight increase with respect to time (aging of fish). The right hand side (rhs) of (14.1) is the marginal user cost (opportunity cost), consisting of the capital loss due to discounting and to the instantaneous mortality. Thus, the lhs of (14.1) is the marginal revenue from keeping the natural capital in the cage and the rhs is the marginal (opportunity) cost of keeping the fish in the cage[39]. Another way of writing the *FOC* is the following, where we have divided in (14.1) with the value per fish, *pw*:

$$\frac{p'(w)}{p(w)}w'(t) + \frac{w'(t)}{w(t)} = [\delta + M] \tag{14.2}$$

This is illustrated in Figure 14.2 where the marginal gain per fish, from growth, is downward sloping and the marginal cost per fish is constant. To simplify the figure and the analysis we now assume that the fish price (e.g. USD/kg) is independent of fish age. Thus, *p'(w)=0,* in both Figure 14.2 and Figure 14.3. Compared to the simple Fisher condition above we have now explicitly considered that some fish die in captivity, and conclude that this accelerate the harvest the same way as the discount rate does. In addition, the price change and growth of fish are taken care of in equation (14.2). The lhs of (14.2) is the relative value growth of one fish. This is shown as the (uppermost from the left) declining curve in Figure 14.2, where the horizontal line represents the rhs of equation (14.2), the marginal loss of postponing harvest. Thus, the optimal time of harvest is when the relative marginal value growth of one fish equals its marginal opportunity cost as capital plus its relative natural loss from mortality (the optimal age of harvest is t^*). Higher δ and M means harvest at an younger age.

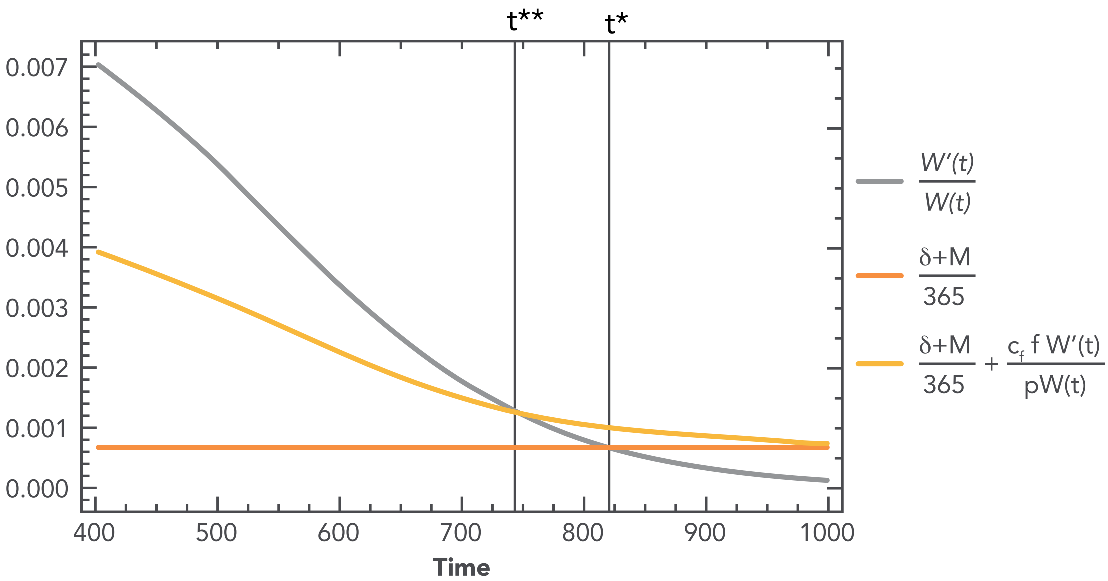


Figure 14.2 The optimal age of harvest with opportunity cost of capital and fish mortality included is t*, and this changes to t** when also feed cost is included.

14.2 RECRUITMENT COST

So far, the economic issues of discounting, mortality and fish price have been analyzed, whereas recruitment was included without any costs. However, juveniles do not come for free (see Table 11.2) and we will now include this cost by adding a fixed cost per recruit, c_r, in the present value function above. First, with R recruits the total recruitment cost is $C_r = c_r R$, and the problem now is $MAX_t\, \Pi(t) = V(t)e^{-rt} - C_r$. The way this is formulated does not imply any change in the *FOC* derived above. Thus, the results discussed in equations (14.1)–(14.2) and in Figure 14.2 still hold (the optimal age of harvest is t^*, recalling the assumption p'=0). Recruitment costs are sunk costs as soon as the R juveniles are put into the cages, and the optimal time of harvest is unaffected of this.

However, if the fish farmer can vary the number of recruits, which is usually the case, the wealth maximisation will result in R being dependent on the cost of recruits. In this case, the optimal R will decrease with an increase in the cost of juveniles (Bjørndal, 1988). The reason for this is that the wealth, the present value of the net profit, depends on the value of the harvest minus the costs of the recruits at the time of investment in the fish capital. The fish capital depreciates through the opportunity price of capital and the mortality. The optimal time of harvest is, however, unaffected by the cost of juveniles, due to the sunk cost argument discussed above. This is for one production cycle of fish. However, recruitment cost will affect the optimal age of harvesting when we consider many rotations simultaneously, and we shall return to this issue below.

14.3 FEED COST

Feed is the largest cost component in many aquaculture businesses (Table 11.2). To include this in the optimisation problem we have to include the feed cost from the time juveniles are released into the cage until the time of harvest. The feed conversion ratio (rate) (FCR) is a measure of an animal's efficiency in converting feed mass into increases of the output, such as kg of fish. FCR is the ratio of inputs to outputs; it is the inverse of "feed efficiency" which is the ratio of outputs to inputs. Let us use the symbols f_t=*FCR*, *F(t)* is feed per unit of time and, as previously, *w'(t)* is the marginal fish growth per unit of time. To simplify we assume that f_t is constant, equal to *f*, throughout the fish life span. The feed quantity per fish at time (age) *t* is then: $F(t) = fw'(t)$ and the FCR is $f = \frac{F(t)}{w\prime(t)}$.

Let the cost per unit feed c_f be constant. By combining this with the feed quantity the total feed cost per unit of time is $C_f = c_f F(t) N(t) = c_f f w'(t) R e^{-Mt}$. Thus, the feed cost develops with the growth of individual fish and the declining number of fish due to mortality. The total feed cost throughout the grow out of one cohort until slaughter has to be deducted from the harvest value to get the net value. The wealth of one cohort at the time of release of juveniles requires discounting of both the harvest value and the feed cost. Wealth maximization of the fish farm with one cohort, with respect to the date of slaughter, gives the following FOC (Annex A):

$$\frac{p'(w)}{p(w)} w'(t) + \frac{w'(t)}{w(t)} = [\delta + M] + \frac{c_f F(t)}{p(w)w(t)}. \qquad (14.3)$$

This resembles equation (14.2) except for the last term on the rhs. Feed cost adds to the costs in a similar way as the discount rate and the mortality[40]. Recall the assumption of size (age) independent fish price (*p'(t)= 0* for all actual *t*). Graphically the previous marginal cost curve in Figure 14.2 shifts upward and the optimal age of slaughter is reduced; this is demonstrated in Figure 14.2 where the optimal age of harvest reduces from t^* to t^{**}. The feed cost term in (14.3) $\frac{c_f F(t)}{p(w)w(t)} = \frac{c_f f w\prime(t)}{p(w)w(t)}$ can be rewritten where the numerator tells how much feed cost it takes to grow an extra unit of fish biomass. This divided by the value of one fish gives the relative marginal feed cost of keeping the fish in the cage and let it grow. Thus the rhs of (14.3) gives for time *t* the marginal cost of continuing growing the fish; consisting of the opportunity cost of capital, the relative natural loss from mortality and the relative feed cost.

14.4 HARVEST COST

Table 11.2 shows that slaughter costs, including freight, for salmon in Norway in 2016 corresponds to almost 10% of the production costs per kg fish. Analytically there are mainly two simple ways of including harvest cost in the objective function. Either as a fixed cost per kg of fish, c_p, or as a fixed cost per fish, c_h. In the former case the cost is deducted from the price and the net price, $p(w)$-c_p, will enter the FOC (14.1) instead of the price $p(w)$. In the latter case total harvest cost equals $c_hN(t)$ and this has to be deducted in the objective function. The FOC in this case is (see Appendix B)

$$\frac{p'(w)}{p(w)}w'(t)+\frac{w'(t)}{w(t)}=[\delta+M][\frac{p(w)w(t)-c_h}{p(w)w(t)}], \tag{14.4}$$

that implicitly gives the optimal time of harvest with a fixed cost per kg. The marginal revenue, on the lhs of (14.4), is the same as in the basic case in (14.2). Thus, the downward sloping marginal revenue curve is the same as in the basic case in Figure 14.2. On the other hand, the marginal costs on the rhs of (14.4) is smaller than in the basic case in (14.2). In a figure like Figure 14.2 this would imply an upward sloping curve below the horizontal line δ+M. In this case the harvest cost reduces the net value of the fish capital and it pays to wait somewhat to realise the capital by harvesting, compared to the no harvest cost case. This is due to discounting and mortality. To summarize, a constant harvest cost per kg fish does not affect the optimal harvest age, whereas a constant harvest cost per fish increases the optimal age, according to equation (14.4).

14.5 ROTATION ISSUES

So far, we have discussed optimality conditions for the release and harvest of one cohort. However, as soon as one cohort is harvested it gives room for the next one to be released into the cage, either immediately or after a period if the facilities need rest, cleaning or repair. Since fish grows relatively slower with age (Figure 14.1), harvest of older fish may give room for younger and faster growing fish and this should be considered simultaneously with the economic issues discussed above. A sequence of rotations should be studied to the best utilisation of the total capital, including the important fish capital, physical capital and site capital. The site has a value in itself since good locations for aquaculture are in limited supply, both for earthen ponds and floating sea cages. Assuming that the parameters are constant across time, all the rotation periods will be of the same length, and each optimal rotation period proves to be shorter than the Fisher period. Following the previous notation *V(t)* is the value of fish at time *t* (age), disregarding the explicit costs of recruitment, feed and slaughter. Instead of the simpler Fisher rule we now have (Annex C):

$$V'(t) = \delta V(t) + \frac{\delta V(t) e^{-\delta t}}{1-e^{-\delta t}} = \delta V(t) + \delta \frac{V(t)}{e^{\delta t}-1} \tag{14.5}$$

where V'(t) is the marginal change in fish biomass value and δ *V(t)* is the opportunity cost of the fish biomass capital. Implicitly we can find the optimal rotation length t^{**} from equation (14.5). The second term on the rhs of (14.5) is the site value, and multiplied by the interest rate this gives the opportunity cost of the fish farm itself. This warrants some further comments. Recall that the present value of an eternal stream of *A* dollars annually at the instantaneous interest rate of δ is $\frac{A}{\delta}$, with δ as a fraction (see chapter 4). The value of one dollar investment today at time *t* is $e^{\delta t}$, and $e^{\delta t} - 1$, the denominator of the last term on the rhs of (14.5), is the added value at time t of one dollar investment today. The harvest value in aquaculture, *V(t)*, emanates at the end of each rotation period, and not (usually not) annually as *A* in this example. The actual rotation period may be more than a year (salmon) or shorter (tropical shrimp and pangasius).

The rotation rule from (14.5) is called the Faustmann rule, after Martin Faustmann (1822–1876), a German forester who in 1849 formulated this problem for forestry where trees grow in a similar way as fish, but at a much slower pace (Pressler, 1860 solved this problem mathematically). An alternative way of formulating the Faustmann equation is on the relative form

$$\frac{V'(t)}{V(t)} = \frac{\delta}{1-e^{-\delta t}}. \tag{14.6}$$

From the discussion above we know that the lhs of (14.6) declines with *t*, as illustrated in Figures 14.2 and 14.3. Going back to the basic problem behind Figure 14.2, $MAX_t\ \Pi(t) =$

$V(t)e^{-\delta t} = p(w)w(t)Re^{-Mt}e^{-\delta t}$, and using this in the Faustmann rule (14.6) we find for constant p, $p'(w)=0$, (see annex C):

$$\frac{w'(t)}{w(t)} = \frac{\delta}{1-e^{-\delta t}} + M. \quad (14.7)$$

We recognize the lhs of equation (14.7) graphically as the downward sloping relative growth curve in Figure 14.3 (also in Figure 14.2). The rhs of equation (14.7) is also downward sloping, asymptotically towards $\delta+M$. This implies that the optimal rotation period is shorter when many rotations are included in the analysis instead of just a single cycle.

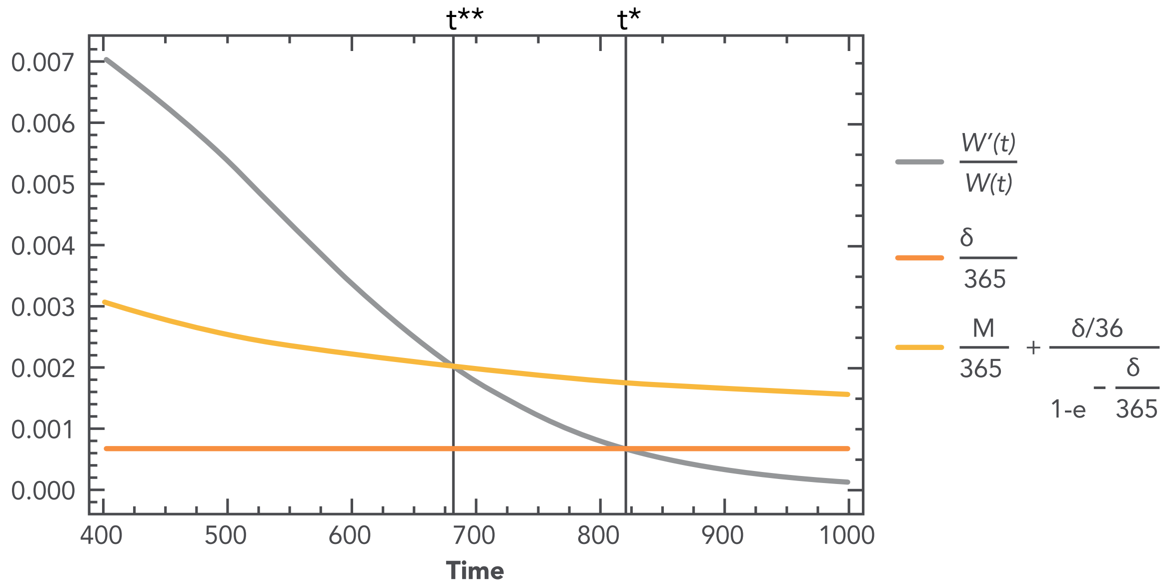


Figure 14.3 The optimal age of harvest with (t**) and without (t*) considering multiple rotations. The single rotation optimum is the same as in Figure 14.2.

As noted above the main three types of capital in aquaculture are fish capital, physical capital and site capital. Disregarding the physical capital, to simplify, the distinction between fish and site capital is demonstrated by the Faustmann rule in (14.5). If, underlining if, the optimal rotation period had been one year the value of the aquaculture farm would have been $\frac{V(t=1)}{\delta}$, whereas $\frac{V(t)}{e^{\delta t}-1}$ is the net value of the farm in the general case. Note that the rotation time t in (14.5)–(14.7) is endogenous, to be derived from this analysis; for fast growing tropical fish, such as tilapia, pangasius and shrimp, the rotation period is usually well below one year, whereas for temperate species, such as salmon, the rotation time traditionally has been two-three years.

As discussed above recruitment cost does not affect the FOC for the optimal time of harvesting in the case of just one production cycle. However, in the case of many rotations recruitment cost matters. To simplify, let the cost of one batch of recruits equal $C_R=c_R R$ with c_R as the unit cost per recruit and the number of recruits R is given. The recruitment costs appear at the beginning of each rotation, at $t=0,\ t,\ 2t,\ 3t,\ldots,\infty$. Instead of equation (14.6) we now get (see appendix C)

$$\frac{V'(t)}{V(t)-C_R} = \frac{\delta}{1-e^{-\delta t}}. \tag{14.8}$$

This implies that the optimal rotation time decreases, compared to rotation without recruitment cost. Thus, recruitment cost affects the Faustmann-solution whereas the Fisher-solution does not change. Equation (14.8) implicitly gives the optimal rotation length when recruits are costly. This is generally the case in aquaculture, whereas in forestry trees in the wild can seed themselves. In aquaculture, grow out firms can to some extent choose what size of recruits to use, but cost will increase with size, whether purchased in the market or produced internally. The growth curve in Figure 14.1 is based on a recruit weight of 120 gram (Annex D) for our model Atlantic salmon, at a 2016 cost of about 1.5 USD. Research and experimentation with bigger smolt is under way in several countries, not just to increase the turnover rate of cohorts, but also to make the fish less vulnerable to sea lice and diseases. In the case of Norway, increased recruit size may also come as a result of the maximum allowable biomass (MAB) regulatory restriction to maximise annual production per unit MAB (chapter 13). The larger smolt the shorter time is needed in the sea for the salmon to reach commercial slaughter weight. Thus, the development of larger recruits in the salmon industry is partly a result of biotechnical and commercial characteristics and partly an adaptation to the current licensing system, in the case of Norway.

We simplified the optimisation problem of rotation, by leaving out the cost of recruits, feed and slaughter, to derive equations (14.5)–(14.8). For computation of the site value, we will first use the net farm gate value of one cohort fish and equation (14.5) to find the optimal age of slaughter, t^{**} in Figure 14.3. Note that on the lhs of (14.5) the marginal change in fish capital appears. Thus, an estimate of this is needed for the computation of t^{**}. When t^{**} is derived, this and the net farm gate value of one cohort fish can be used to find the site value:

$$S(t^{**}) = U(t^{**})/(e^{\delta t^{**}} - 1), \qquad (14.9)$$

where $U(t)$ is the net farm gate value of one cohort.

If we have all data, such as the net farm gate value of one cohort fish, the costs of recruits, feed, chemicals, medicine, labour, slaughter, and capital, as well as the growth and mortality data in a spreadsheet, models and formulas can be designed in line with the theory outlined above. This way t^{**} and $S(t^{**})$ as well as other endogenous variables can be found.

14.6 SEASONAL ISSUES

We have seen that aquaculture takes place in both tropical, temperate and arctic areas of the world. The further north and south the more important are seasonal variations in temperature for the intra-annual cycle of fish growth (for aquaculture salmon, see Thyholdt, 2014; for a theoretical discussion, see Flaaten, 1981). In this chapter, we have simplified the analysis by excluding seasonal variation in growth. However, for actual plant operation seasonal growth may be of utmost important for the optimization of the intra-annual period of harvest. For temperate and arctic fish such as salmon, the growth is highest in summer time when the water is warmer (Jobling, 2003). Also in tropical areas, growth of fish may vary intra-annually due to factors such as seasonal variations in salinity, oxygen, infections and predation. In addition, tropical storms, and changes between rainy and dry seasons can have important bearings on actual farm management.

In addition to seasonal factors on the supply side, there may also be seasonal variations on the demand side, influencing the actual seasonal production and market supply. Seasonal changes in demand are quite common for easily perishable food such as fresh fish (Wessels and Wilen, 1994). For salmon, demand is stronger before holiday seasons such as Christmas and Easter. Similar examples are found for pangasius, tilapia and shrimp in Vietnam and other Asian countries, related to both calendar and religious festivities.

In the wild fish mature, eventually, and this require a significant amount of energy for roe production instead of fish muscle. In aquaculture, producers try to avoid maturation of the fish since the feed energy would transform mainly into roe, which is usually not what the farmer can sell profitably. Thus, in many cases fish maturation will have a bearing on the management plan of the aquaculture plant, both in the tropical and temperate zones, as well as in the Arctic areas. Overall, actual management plans will include seasonal variations in markets, fish growth and maturation. It does not pay to harvest and sell fish well before a price increase, nor wait until after maturation.

14.7 ECONOMIC RENT IN AQUACULTURE (ERA)

In theory ERA is any payment to a farm and site owner, on land or sea, in excess of the costs needed to bring that farm into production. However, for analytic and policy purposes it may be useful to distinguish among different types of ERA. Aqua-land is an inelastic factor of production, at least for good quality locations. In principle locations could be ranked from the very best one suited for aquaculture farming to the marginal one where hardly anyone would be interested in establishing a farm; due to for example, water quality, biotechnical productivity or distance to the input and output markets. The surplus that arises due to the difference between the marginal and intra-marginal location is the differential rent (Ricardo-rent – Ricardo, 1821). In a way, this corresponds to the intra-marginal rent in fisheries, discussed in chapter 7, but with the important difference that in aquaculture and agriculture this rent usually arises from differences in the natural capital and beneficial distance to the input and output markets. In fisheries, it is mainly due to differences in the manmade capital, such as vessels and fishing gear, and the operational skills of skippers and crew (Duy et al., 2010). Of course, also in aquaculture operational skills can cause profitability differences among farms, but this is not differential rent in the Ricardo-sense.

We have discussed rotation issues above and seen that since any cohort can be harvested to give space to the next one, each location gets a special value from the perpetual rotations of even-aged fish. This value of the location is termed Faustmann-rent (Faustmann, 1849; Guttormsen, 2008). A third type of ERA is quasi-rent that differs from pure ERA in that it is a temporary phenomenon; it can arise from the barriers to entry that potential competitors face in the short run from such as the granting of licenses by governments (this is the Marshall-rent – Marshall, 1890).

In this and the previous chapters we have seen that governments can issue licenses to firms to establish aquaculture farms, and that such institutional arrangements may limit the number of farms compared to open access and free markets. If the aquaculture industry faces downward sloping demand for its products, limitation of the number of licenses may limit the output of fish, thereby increasing the price compared with that of perfect competition. This is the case whether the official arguments for a licensing system is environmental protection or market reasons. Thus, some returns are associated with legally enforced monopolies, oligopolies or cartels through licensing; market rent arises where there is downward sloping demand for the aquaculture product. If this is on a permanent basis, let us simply call it oligopoly rent, as opposed to the short run Marshall rent.

In Table 11.2, we presented some key data on revenue, cost and profit of three aquaculture industries, and the bottom line showed profit margins of 5.1, 9.5 and 33.1 percent for pangasius, shrimp and salmon, respectively. Based on this, and the discussion above, we may ask if there is any economic rent in the three industries and the relationship between profit and ERA. Which one is the greatest, profit or ERA? Based on a recent paper on rent in fisheries (Flaaten et al., 2017) the corresponding method may be useful for ERA analysis, provided necessary data is available. For salmon in Norway, national and regional data is available and the total figures for 84 companies in 2016 are included in the earnings and costs data in Table 14.1.

Accounting principles for aquaculture firms are about the same as for other firms within a country. However, since rules and regulations vary among countries, actual bookkeeping practices also vary. In small-scale farms in developing countries, owners are barely required to keep official accounts. For research purposes, data has to be collected on a case-by-case basis or compiled from different sources. Variable and fixed costs, as well as financial revenues, expenses, and taxes, affect the result. Note that purchase of rights (licenses and permits), be it through markets, auction or other mechanisms, would be long-term investment, similar to purchasing a floating cage or a riverbank pond. Depreciation of rights (as part of the total operating expenses) affects the operating profit (EBIT in table 14.1). In addition, financial costs of aquaculture rights affect the profit on ordinary activities before tax (EBT in Table 14.1). Thus, both depreciation and financial costs of rights affect EBT. Labour cost, as a part of the total operating expenses, vary among types of aquaculture species and technology, but often it is low. Highest are the costs of feed and recruits (see Table 11.2).

Concept	Explanation	ERA for salmon and trout in Norway, 2016 Million NOK (million USD)
Revenue	Farm gate value of sale of fish.	50,072.3[1] (5,961.0)
- Total operating expenses	Including recruits, feed, chemicals, medicine, labour, energy, slaughter, maintenance, and depreciation of farm, license and permit.	32,035.0
= Operating profit (EBIT)	Earnings before interest and tax.	18,037.3
+ Total financial revenue	Financial income and currency gains.	530.7
-- Total financial expenses	Financial cost and currency rate losses.	495.4
= Profit on ordinary activities before tax (EBT)		18,072.6
+ Depreciation on intangible capital	Intangible capital includes licenses and permits.	-12.5[2]
+ Financial cost of intangible capital	Financial cost (interests, fees) of license and permit purchases.	226.5[3]

Concept	Explanation	ERA for salmon and trout in Norway, 2016 Million NOK (million USD)
-- Calculated interest on equity	The interest rate should equal what is paid on long term loans, or equal to interest on government bonds (opportunity cost).	917.6[3]
= Economic rent in aquaculture (ERA) unadjusted	The residual for the aquaculture industry owners, without deduction of environmental and management cost.	17,369.0 (2,067.7)
Operating margin	EBIT in percent of revenue	36.0
Profit margin[4]	EBT in percent of revenue	36.1
Economic rent margin	ERA in percent of revenue	34.7

Table 14.1 Aquaculture rent (ERA) can be derived from costs and earnings data.
[1] Allmost 90% is Atlantic salmon.
[2] It is a bit odd that this number is negative.
[3] Based on 4.0 % real annual rate of interest recommended by the Ministry of Finance as opportunity cost of capital in long term public investment projects.
[4] From a theoretical point of view, the Profit rate (return on total assets) – with the firm's capital in the denominator – is a better indicator for comparison of profitability among firms. However, for comparisons of the three aquaculture industries in Table 11.2 data deficiencies lead to the use of Profit margin.
Sources: Fiskeridirektoratet, 2017a; Knut Heen, UiT-the Arctic University of Tromsø (personal communication).

As discussed above, aquaculture production in Norway is constrained by government licenses for establishing farms and local permits for the specific location in coastal water. Norwegian produced Atlantic salmon has more than half of the world market, and downward sloping demand exists (Xie et al., 2009; Brækkan et al., 2018). Thus, limits on Norwegian production has an effect on the world market price and the revenue of salmon farms. Brækkan (2014) estimates, within a world market model, that one percent increase in Norwegian salmon production reduces the world market price with about half a percent. The ERA in Table 14.1 is rather high, including oligopoly, Ricardo and Faustmann rents. The economic rent margin (relative ERA) is a little lower than the profit margin (relative EBT), mainly due to the calculated interest on equity. On the other hand, the financial cost of intangible capital works in the opposite direction. Data in Fiskeridirektoratet (2017a) shows that 2016 was an exceptionally good year for the Norwegian salmon industry, in particular due to the high market prices. However, the industry did very well also in 2014 and 2015 with profit margins of 26.7% and 21.4%, respectively, compared to 36.1% for 2016.

What about rent in the Vietnamese aquaculture industries – are there any? We have seen in Table 11.2 that the profit margins were 5.1% and 9.5%, on a kilogram basis, for pangasius and shrimp, respectively; far below that of 33.1% for salmon. How can we explain this? Without further analysis, this author think it is mainly because of two factors, the very limited government restriction on entry of firms and production, as well as greater competition in the world market for products from pangasius and shrimp than for Atlantic salmon. Pangasius is an inexpensive whitefish that compete strongly with other low priced white fish, and Vietnam has, with a market share of about ten percent for shrimp, less market power than Norway has for salmon. Thus, even with restrictions through licensing that effectively could reduce production the author think it would be difficult for Vietnam to influence positively the world market price and industry rent. However, licensing and other technical regulations could contribute to better environmental performance of the industry and more and better paid high quality products, at least for shrimp. To the introductory question of this paragraph, maybe we have to defer it to future research to give a true answer. With reference to the discussion in this chapter and in Chapter 13, several environmental and economic issues await further research.

Total revenue of an aquaculture industry depends on price and quantity determined simultaneously by supply and demand in the global market, as well as of the market situation for substitute products. If there is free entry in a competitive industry, we should not expect much ERA to exist. However, locations may have different biophysical productivity, and managers' skills on operational efficiency may vary, contributing in different degree to Ricardian and Marshallian rent. On the other hand, if, as in the case of Norway, government intervention hamper production growth, both profit and rent can be realised. Above normal profit would attract wannabe farmers and existing farmers would expand production, legally or by circumvention of rules and regulations. Such issues are well recognized from oligopoly and cartel theory. Thus, the existence of ERA or not depends largely on the scarcity of aqua-land, the market conditions for the industry and the regulatory regime.

Aquaculture industry regulations usually aim at handling environmental externalities (Chapter 13), and the hampering of production and growth, contributing to higher market price and ERA, is a positive side effect for the industry. Governmental regulation of the aquaculture industry for environmental externalities does not come for free and public expenses could be recovered from the firms. As long as there is sufficient accounting profit, governments may collect a portion of ERA for the purpose of general public finance; for example, as profit tax, royalties, production fees or location rental taxes.

14.8 THE FUTURE

The aquaculture industry will continue to grow globally (FAO, 2016). There may be temporarily setbacks for some species in some countries, due to environmental problems and diseases, but overall consumers' demand and willingness to pay for seafood will pull fish to the markets. In the long run countries with good institutions to handle environmental stress and fish diseases will probably be most successful. However, we may expect increased production also in several mainly short-sighted laissez faire economy countries, with less focus on environmental sustainable aquaculture. We can hope they will gradually learn from their failures and thus contribute to the supply growth of safe seafood in a sustainable way. Environmental and food safety conscious consumers may contribute to such a development, even though experiences show that they are mainly concerned with product quality and price, and less so for negative externalities from aquaculture production in a country far away.

In the case of salmon in Norway, the system of licensing and environmental regulation has gradually contributed to the high market price and very profitable aquaculture firms. Therefore, in later years, from each firm's perspective further expansion seemed just natural, and very profitable. However, what about the total market and environmental effects if all established firms are allowed to expand production, in addition to some licenses for newcomers? Since environmental problems vary regionally, the policy makers' solutions include overall production increase, but possible reductions in some areas. The coast is divided into thirteen zones and the environmental conditions, with respect to sea lice, within each decides the fate of the area farms. In the zones where the average lice concentration is below the maximum acceptable level, the total allowable biomass will be allowed to increase by six percent. Such zones are associated with the green traffic light. Growth for existing farms is limited to 2 percent each, and the price is 120,000 NOK per tonne (2018). Some farms using more environmental friendly technology will be allowed to increase their biomass by maximum six percent each. For the remaining biomass increase the Ministry plans auction of licenses. Revenues from these actions of expansion, estimated at one billion NOK (about 128 million USD) for 2018, are placed in a fund and aquaculture counties and municipalities will receive 80 percent of the means. On the other hand, in the red traffic light zones where sea lice exceeds the maximum acceptable level, farms will be required to reduce production, however, it remains to see how this will be done.

There is hardly any limit to aquaculture production if farms can go offshore. For salmon and other finfish, such as seabass, seabream, cobia and tuna, technological solutions are developing, partly commercially and partly in research projects. When farms are located some distance offshore, space is plentiful globally, water is deeper and currents are stronger than inshore. Discarded nutrients and faeces that near shore settle on the seafloor below and near the farm, offshore these types of pollution tend to be swept away from the location and diluted. Offshore farms must withstand the high energy impacts of storms and sea currents, as well as attacks from predators such as sea mammals and sharks. To the best of the author's knowledge, the offshore farms so far have been established in national EEZs and are subject to national regulation. This is important to avoid uncontrolled use of antibiotics and other drugs and the possibilities of aqua cultured fish escaping and spreading disease among wild fish. In some cases, such as the USA, there may be some initial problems in regulating the offshore aquaculture farms since coastal states have the regulatory control of the sea extending to 3 nautical miles, while federal waters extend to 200 nm offshore. However, economic history has proved that when technological development lead to new and (expected) profitable production methods, such as transoceanic shipping and offshore oil and gas industries, the institutional framework also developed positively. Currently (2018), research and development for offshore aquaculture takes place in numerous coastal countries, and international organizations, such as the FAO, discuss institutional issues. An internet search for "offshore aquaculture" will give you many examples of technologies and species.

Climate change may affect aquaculture production either directly or indirectly by affecting environmental factors, farming areas, feed availability and markets. The Intergovernmental Panel on Climate Change (IPCC) is a scientific and intergovernmental body first established in 1988. It is under the auspices of the United Nations, and the majority of the world's governments participate in its work. Climate predictions of IPCC have been used by natural scientists and social scientists to discuss fisheries and aquaculture issues for many regions of the world; for a recent overview, in particular for aquaculture, see Nadarajah and Eide, 2018. Generally, the world's fisheries and aquaculture industries are very diverse in terms of natural environments, technologies, species, production and farming systems, markets, scales of operations, and institutional frameworks. Aquaculture farms and industries have different degrees of resilience and vulnerability toward climate change. For fresh and brackish water aquaculture in some Asian countries, it was found that "most of carp, tilapia and shrimp species have the potential of adapting to warming. Carp and tilapia production in coastal areas are vulnerable to seawater intrusion during coastal flooding. Reduced fishmeal supply may constrain shrimp production if it occurs in future. Aquaculture production in the Asian region could adopt climate change impacts with modification of farming systems, technological improvement and expansion of infrastructure facilities in the future", Nadarajah and Eide, 2018. Thus, the diversification of aquaculture across species and geographical areas help keeping up the total production. Similar results were found for Atlantic salmon in Norway (Hermansen and Heen, 2012), but with some shift in the production from the southern part to the north of the country due to sea temperature increase. Globally, the aquaculture industries seem to adapt reasonably well to temperature increase, precipitation change and sea level rise, by technological development and species adaptation. Although some aquaculture areas will be unsuitable for further production, the overall global picture for continued increase in fish production is positive, despite climate change impacts.

Exercise 14.1

Discuss the case of constant harvest cost per kg fish, in equation 14.4, and indicate how this changes the marginal revenue curve in Figure 14.2. Does it matter for the optimal age of harvest whether the harvest cost is constant per kg fish or constant per fish?

Exercise 14.2

What is the site value for each farm when the expected eternal net farm gate value of one cohort is *U(t)*=10, interest rate δ=10% p.a., production cycles of 24 and 6 months for "salmon" and "shrimp", respectively?

Exercise 14.3

Use the data and parameters in the Annex D table to compute, by using for example EXCEL or Mathematica, *t** in Figures 14.2 and 14.3, *t*** in Figure 14.2 and *t*** in Figure 14.3. If necessary, make you own additional or alternative assumptions.

Annex A

Feed cost

This annex demonstrates how to derive the FOC (14.3) to the wealth maximization problem when feed costs are included. The feed needs changes over time due to fish growth and also because the number of fish in one cohort decreases owing to mortality. Total feed at a given point in time is

$$F(t)N(t) = F(t)Re^{-Mt} = fw'(t)Re^{-Mt} \qquad \text{(A14.1)}$$

Fish is fed continuously after being released into the cage and the total feed, *TF*, is found by summarizing the feed from time zero (release) up to t. Mathematically we integrate equation (A14.1)

$$TF_t = \int_0^t F(z)R\,e^{-Mz}dz. \qquad \text{(A14.2).}$$

TF is measured in e.g. kg or ton. Let the cost per unit of feed be constant, c_f. By combining this with the total feed in equation (A14.2) we can find the total (accumulated) feed cost, discounted. Thus the discounted value of total feed costs, DTF_t, is

$$DTF_t = \int_0^t c_f F(z) R e^{-(\delta+M)z}\, dz \tag{A14.3}$$

at the time of releasing R juveniles into the cage. The maximization problem of the fish farm is

$$MAX\ V(t) = p(w)w(t)Re^{-(\delta+M)t} - \int_0^t c_f F(z) R e^{-(\delta+M)z}\, dz, \tag{A14.4}$$

with respect to t and $0 \le t \le T$, anticipating there is an upper time limit to aqua culturing the fish due to biological or economic factors.

The FOC for this maximisation problem is (the student should check that this is correct)

$$p'w'w + pw' = pw(\delta + M) + c_f F(t). \tag{A14.5}$$

This resembles equation (14.1), but on the rhs there is now an extra term taking care of the feed costs. Divding (A14.5) by the value per fish, pw, we have

$$\frac{p'(w)}{p(w)} w'(t) + \frac{w'(t)}{w(t)} = [\delta + M] + \frac{c_f F(t)}{p(w)w(t)}, \tag{A14.6}$$

Thereby we have proved (14.3), that resembles equation (14.2) except for one term. The last term on the rhs can be rewritten $\frac{c_f F(t)}{p(w)w(t)} = \frac{c_f f w\prime}{p(w)w(t)}$ where the numerator tells how much feed costs it takes to grow an extra unit of fish. This divided by the value of one fish gives the marginal feed cost to keep the fish in the cage and let it grow.

Annex B

Harvest cost

Assuming harvest cost per fish is given, equal to c_h, the wealth to be maximised is

$$MAX\ V(t) = [p(w)w(t) - c_h]Re^{-(\delta+M)t}, \text{ with respect to } t,\ 0 \le t \le T. \tag{B14.1}$$

The FOC is

$$\frac{p'(w)}{p(w)} w'(t) + \frac{w'(t)}{w(t)} = [\delta + M][\frac{p(w)w(t) - c_h}{p(w)w(t)}], \tag{B14.2}$$

that implicitly gives the optimal time of slaughter in this case.

Annex C

Rotation

At the beginning of each rotation, when juveniles are released into the cage, the present value for that particular rotation is $\Pi(t) = V(t)e^{-\delta t}$. In other words, since all rotations are of the same length, the present value of the profit of n rotations at the time of release of the first cohort is

$$\pi_n(t) = V(t)e^{-\delta t} + V(t)e^{-2\delta t} + \cdots + V(t)e^{-n\delta t} = V(t)e^{-\delta t}(1 + e^{-\delta t} + e^{-2\delta t} + \cdots + e^{-(n-1)\delta t}) = V(t)e^{-\delta t}A, \text{ where} \quad \text{(C14.1)}$$

$$A = 1 + e^{-\delta t} + e^{-2\delta t} + \cdots + e^{-(n-1)\delta t}$$

In principle the number of rotations is unlimited. From the math course we know that A is an geometric series and that the infinite geometric series has the solution (e.g. Sydsæter et al., 2010)

$$\lim_{n\to\infty} A = \frac{1}{1-e^{-\delta t}}. \quad \text{(C14.2)}$$

Combining (C14.1) and (C14.2) we have for the infinite horizon case

$$\pi_n(t) = V(t)e^{-\delta t}\frac{1}{1-e^{-\delta t}}. \tag{C14.3}$$

The first order condition for maximum is (the reader should check that this is correct)

$\frac{(1-e^{-\delta t})(V'(t)e^{-\delta t}-\delta V(t)e^{-\delta t})-V(t)e^{-\delta t}\delta e^{-\delta t}}{(e^{\delta t}-1)^2} = 0$, that implies (the numerator equal to zero)

$$V'(t) = \delta V(t) + \frac{\delta V(t)e^{-\delta t}}{1-e^{-\delta t}} = \delta V(t) + \frac{\delta V(t)}{e^{\delta t}-1}. \tag{C14.4}$$

This is a well known equation in forest economics where the rotation problem was formulated by the German forester M. Faustmann in 1849, and was simplified and solved mathematically in Pressler, 1860. An alternative way of writing (C14.4) is on the relative form

$$\frac{V'(t)}{V(t)} = \frac{\delta}{1-e^{-\delta t}}. \tag{C14.5}$$

Recall the capital growth when the value of fish at time *t* depends on individual weight, number of fish, and price of fish. The optimisation problem in aquaculture is

$$MAX_t\ \Pi(t) = V(t)e^{-\delta t} = p(w)w(t)N(t)e^{-\delta t} =$$

$$p(w)w(t)Re^{-Mt}e^{-\delta t} = p(w)w(t)Re^{-(\delta+M)t}, \tag{C14.6}$$

and using this in the Faustmann rule (14.5) and (C14.5) we find, suppressing time *t*,

$$V' = (p'w + pw')N - pw(\delta + M)Re^{-Mt}. \tag{C14.7}$$

For constant price of fish, $p'(w)=0$,

$$V' = pw'Re^{-Mt} - pw(\delta + M)Re^{-\delta t}. \tag{C14.8}$$

And further,

$$\frac{V'(t)}{V(t)} = \frac{pw'Re^{-Mt}-pwMRe^{-\delta t}}{pwRe^{-\delta t}} = \frac{pw'Re^{-Mt}}{pwRe^{-\delta t}} - M. \tag{C14.9}$$

Combining this with (C14.5) we have

$$\frac{w'(t)}{w(t)} = \frac{\delta}{1-e^{-\delta t}} + M, \tag{C14.10}$$

the Faustmann rule in aquaculture with fish growth and in the presence of natural mortality.

An alternative way of writing the Faustmann rule in (C14.5) is

$$V'(t) = \delta V(t) + \delta \frac{V(t)}{e^{\delta t} - 1} \text{ (the reader should verify this).} \quad \text{(C14.11)}$$

Let us now return to the issue of recruitment cost and multiple rotations. With constant recruitment cost per rotation C_R, we introduce this in equation (C14.1) to get

$$\pi_n^R(t) = C_R + (V(t) - C_R)\, e^{-\delta t} + (V(t) - C_R)e^{-2\delta t} + \cdots + (V(t) - C_R)e^{-n\delta t} = C_R + (V(t) - C_R)e^{-\delta t}\left(1 + e^{-\delta t} + e^{-2\delta t} + \cdots + e^{-(n-1)\delta t}\right) = (V(t) - C_R)e^{-\delta t}A, \quad \text{(C14.12)}$$

where A is defined in (C14.1) and (C14.2). The first non-discounted C_R is the recruitment cost of the first cohort when the fish farm is established. Using the same procedure as above, we arrive at the FOC for maximum π_n^R

$$\frac{V'(t)}{V(t) - C_R} = \frac{\delta}{1 - e^{-\delta t}}. \quad \text{(C14.13)}$$

The discussion of this is found in the main text.

Annex D

Fish growth

Stylized logistic salmon growth, used for Figures 14.1-14.3 is

w(t) is the weight at age *t*

w'(t)=dw(t)/dt

w_∞=maksimum weight of fish, w_o=weight of recruits (smolt) at release time *t=0.*

$$w(t) = \frac{w_\infty}{\left[1 + \frac{w_\infty - w_0}{w_0} e^{-rt}\right]} = \frac{w_\infty}{[1 + ke^{-rt}]} \quad \text{(D14.1)}$$

$$\frac{w'(t)}{w(t)} = \frac{\frac{w_\infty - w_0}{w_0} r}{\left[\frac{w_\infty - w_0}{w_0} + e^{rt}\right]} = \frac{kr}{[k + e^{rt}]} \quad \text{(D14.2)}$$

Parameters for figures 14.1–14.3

	Symbol	**2015~rounded used**
Intrinsic growth rate, per day	r	0.009
Maximum weight of fish	w_∞	16.0 (kg)
Weight of recruits	w_0	0.12 (kg)
Relative growth potential after release	$k = \frac{w_\infty - w_0}{w_0}$	
Price of fish	p	34.57~34.50 NOK/kg
Harvest cost per fish	c_h	2.95*4.55=13.42~13.50 NOK/fish
Feed cost	c_f	13.18~13.20 NOK/kg
Feed conversion rate	f	1.2
Interest rate, annual (per day)	δ	0.10 (δ/365)
Mortality rate, annual (per day)	M	0.15 (M/365)

Sources: Economic parameters for 2015 – Directorate of fisheries (2016); other parameters: own calculations based on Jobling (2003), Olsen and Hasan (2012), Thyholdt (2014). The author is the only one to blame for any miscalculations.

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ENDNOTES

1. See e.g. Andersen (1981) for a bioeconomic analysis of price uncertainty, and Flaaten et al. (1998) and Jensen (2008) for overview and analyses of several types of uncertainty in fisheries.
2. For alternative texts and further reading see Anderson (1986), Clark (1990) and Hannesson (1993).
3. Pitcher and Hart (1992) give a thorough review of fisheries biology and fisheries biological models as well as a review of fish stocks globally. Hamre (1986) and Pedersen and Mikkelsen (2018) give reviews of fish stocks in the North Sea and Norwegian waters, in addition to fish exploitation theory.
4. Measuring of fishing effort can be complicated. For a scientific contribution, see Squires (1987).
5. Substitution between inputs in the effort production function (2.2) have proved to create problems in actual fisheries management where one or a few inputs are restricted – see Dupont (1990).
6. A common definition of capacity often used in productivity studies is that of Johansen (1968): "The maximum amount that can be produced per unit of time with existing plant and equipment, provided the availability of variable factors of production is not restricted".
7. However, one corner solution in figure 3.2 would be zero effort and the virgin fish stock, in the case where effort cost is too high for there to be an intersection between the MC(E) and the AR(E) curves. Another corner solution would be for zero effort cost, implying extinction of the stock and zero effort after the "extinction process" is finished.
8. Our use of only two firms is of course to make the model and the discussion as simple as possible, even though we know it takes more than two to create a competitive market.
9. The following part of this section is adapted from OECD (2000) where the target state of fisheries is called responsible fisheries. FAO (1995) describes the concept of "responsible fisheries" and its development. Discard of fish and other unwanted/illegal adaptations to regulations by fishermen are discussed in the literature, including in Jensen and Vestergaard (2002).
10. Sometimes intra-marginal rent refers to rent related to the average total cost curve, shown in figure 6.2. However, the main point is that intra-marginal rent is a surplus that accrues to those vessels that are more cost efficient than the marginal one.
11. Ex-ante, before a vessel is designed and built, the owner has a wide range of sizes and technological solutions to choose from, but ex-post, after completion, the vessel's major technical characteristics, such as length, weight, hold size and engine power are fixed. Thus we may say that a fishing vessel capacity is flexible ex-ante, but not ex-post, whereas fishing effort is flexible also ex-post. Such characteristics of production is often called "putty-clay" – can you guess why? (see Johansen, 1972). How flexible effort is depends on the technical characteristics built in to the vessel. Effort measured in days and hours of fishing is definitely variable ex-post.
12. With fixed cost, k, quadratic variable cost of effort curve $vc(e) = ae^2$ and total cost $tc(e) = ae^2 + k$, we get the linear marginal cost curve $mc(e) = 2ae$.
13. Note that with variable cost of effort equal to $vc(e) = ae^2$, average variable cost is $avc(e) = ae$, which is a straight line with half the slope of $mc(e) = 2ae$ shown in figure 6.3. Thus in this particular case there is no intersection between $mc(e)$ and $avc(e)$ to act as the short-run brake on vessel operations.
14. Producer's surplus in fisheries was discussed first in Copes (1972).

15. This sub-chapter is based on, with some direct quotations from, Flaaten and Mjølhus, 2010 and Reithe et al., 2014. These two articles give many references to the a quite comprehensive literature on MRs, including Holland and Brazee,1996; Hannesson, 1998; Conrad, 1999; Sanchirico and Wilen, 2001; Pezzy et al., 2003; Grafton et al., 2005; Armstrong (2007).
16. Even though both catchability coefficients are denoted by q, they differ because of the difference between X and $X_H/(1-m)$.
17. Migration of a schooling species between two parts of its habitat area may however have other causes than those discussed here with density difference as the driving force.
18. The m needed to keep the stock above a specific level depends on economic, biological and technical parameters – for details see Flaaten and Mjølhus, 2010 and Reithe et al., 2014.
19. For the proof see Flaaten and Mjølhus, 2010.
20. Pezzey et al., 2000 mention additionally, in the case of marine reserves, the possibility of a shift in demand caused by "more desirable fish". However, this is not pursued in this book.
21. Recall figure 4.1, which shows the discount factor for discrete and continuous time. By adjusting the discount rates to each other the discount factors may be almost the same.
22. For calculation of yield per recruit, the number of recruits is usually estimated at the age of first capture and not at the age of zero. This means that for the cod example shown in figure 8.5, the number of recruits would equal $N(3)$ since three-year old cod is about the smallest size to be caught in commercial fisheries using the legal minimum mesh size. In the case of Northeast Arctic cod, $N(3)$ = 605 million is the mean recruitment for 1950–1982 (Jacobsen, 1992).

23. This concept was introduced in Beverton and Holt (1957). Dictionaries tell that "eu" is a prefix meaning "good", "well", occurring chiefly in words of Greek origin.
24. When cost per unit effort increases with effort, implying the existence of intra-marginal rent (IMR) in the OA fishery, the total IMR may increase as a result of technical regulations only.
25. Welfare economic measurement is more complex in the case of multispecies harvesting (see Vestergaard, 1999).
26. This stock comprises the minke whale in the North Sea, Norwegian coast, Norwegian Sea, Barents Sea and Spitsbergen area.
27. The term "per capita" is used, even though we mean per unit of biomass.
28. In a logistic single species model, the equilibrium stock level with no harvesting always equals the carrying capacity.
29. In the case of a quadratic and strictly concave utility function this gives rise to a linear demand structure (Singh and Vives, 1984). For the case of two goods the implication is that the demand for permits reduces to equation (10.1) when there is no explicit price of the quality.
30. Since most of the salmon die after spawning, Olaussen and Skonhoft (2008) and others use another type of biological recruitment model.
31. We could of course have combined the effects on the stock from angling and commercial fishing, but have chosen to stick to the former only to keep the analysis as simple as possible.
32. The main sources of the facts are FAO, 2016; FAO, 2017; Wikipedia. Other sources are specified in the text.
33. There are other places and modes of production of shrimp in Vietnam where the seed cost varies between 2 per cent and 40 per cent of total cost (Thi Thanh Ngan Le, UiT, The Arctic University of Norway, personal communication).
34. Smoltification (also known as Parr-Smolt transformation) is the series of physiological changes where juvenile salmonid fish (parr) adapt from living in fresh water to living in seawater (smolt). In the wild it is only when it's 2–5 years old that it smoltifies and migrates into the ocean. Physiological changes during smoltification include altered body shape, increased skin reflectance (silvery coloration), and changes in the gills to adapt osmoregulation to salt water. This occurs when the water temperature rises above approx. 8 degrees, most often from the beginning of May (South Norway) and gradually further north as the temperature rises over the spring. At the emigration the smolt is between approximately 13 cm and 15 cm long.
35. Vaccines against two other bacterial diseases, winter ulcers – *Moritella viscosa* and Yersiniosis – *Yersinia ruckeri*, and against one more virus disease, infectious pancreatic necrosis (IPN), are approved for use. Vaccines against infectious salmon anaemia – ISA-virus – do not have a general approval by the Norwegian Medicines Agency, and vaccination against this disease can only be done with a special permission for each case.
36. Ten laws and 55 regulations with more than 900 paragraphs, managed by the Food Safety Authority and other agencies, is the main legal framework the salmon aquaculture industry has to obey (2013) to operate in the business (Norsk Fiskerinæring, 2013).
37. In 1985 coastal municipalities got the opportunity to plan their sea areas inside the baselines, i.e. the straight lines connecting the outermost reefs and islands. In 1989, the area was extended by one nautical mile (1852 m). Thus, the planning responsibility should coincide with EU's Water Directive that Norway has also acceded. In practice, this means that the municipalities now reign over an area of

about 100,000 km^2. Here, municipalities allocate space for aquaculture (A-sites) or create multipurpose areas where aquaculture is included as one of several possible activities (Hersoug and Mikkelsen, 2018).

38. Compare the optimality condition of aquaculture in equation (14.1) to that of wild fish in (4.18) to see the similarities and differences.
39. Compare this optimality condition of aquaculture in equation (14.2) to that of wild fish in (4.18) to see the similarities and differences. Feed cost is one of the most important differences.
40. The major viruses of concern (in estimated order of past economic impact for Thailand) are white-spot syndrome virus (WSSV), yellow-head virus (YHV), hepatopancreatic parvovirus (HPV) and monodon baculovirus (MBV). However, with the introduction of P. vannamei, Taura syndrome virus (TSV) and infectious hypodermal and hematopoeitic virus (IHHNV) have now become important" (Flegel, 2006). And it has become worse: "Several shrimp diseases are new or newly emerged in Asia, including acute hepatopancreatic necrosis disease (AHPND), hepatopancreatic microsporidiosis (HPM), hepatopancreatic haplosporidiosis (HPH), aggregated transformed microvilli (ATM) and covert mortality disease (CMD). In addition to these, white spot disease (WSD), yellow head disease (YHD) and infectious myonecrosis (IMN) continue as the most serious viral threats to shrimp farmers in the region. Other diseases such as monodon slow growth syndrome (MSGS), white tail disease (WTD) and abdominal segment deformity disease (ASDD) are of less concern (Thitamadee et al., 2016).