Essays on the Economics of Fisheries Management

by

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Table of Contents

Introduction **1**
References 14

1 Uncertainty in Bioeconomic Modelling **17**
1.1 Introduction 19
1.2 Stochastic Bioeconomic Models 20
1.2.1 A Discrete-Time Model 21
1.2.2 A Continuous-Time Model 23
1.3 Applications in Bioeconomics 26
1.3.1 Optimal Harvest from a Fish Stock 27
1.3.2 Relative Efficiency of Management Instruments . . . 31
1.3.3 Management of Shared Fish Stocks 37
1.3.4 The Risk of Biomass Collapse 38
1.3.5 Spatial Bioeconomic Models and Marine Reserves . . 40
1.3.6 Other Issues 45
1.4 Concluding Remarks 46
References 48

2 Supply Functions for North Sea Herring **55**
2.1 Introduction 57
2.2 The Bioeconomic Model 59
2.2.1 The Herring Fishery 59
2.2.2 The Bioeconomic Model 60

2.3 Empirical Analysis . . . 67
2.3.1 The Equilibrium Supply Curves . . . 72
2.3.2 Sensitivity Analysis . . . 75
2.4 Effects of Regulations . . . 75
2.4.1 Regulations 1981-1996 . . . 76
2.4.2 Regulations 1996-2002 . . . 78
2.4.3 The Effect of the 1996 Change in Regulations . . . 81
2.5 Summary . . . 83
References . . . 86

3 Stochastic Modelling of the North Sea Herring Fishery 89
3.1 Introduction . . . 91
3.2 Bioeconomic Model and Empirical Analysis . . . 92
3.2.1 The North Sea Herring Fishery . . . 93
3.2.2 The Model . . . 94
3.2.3 Empirical Analysis . . . 101
3.3 Numerical Analysis . . . 106
3.3.1 Model 1: The Spence Production Function . . . 107
3.3.2 Model 2: The Cobb-Douglas Production Function . . 115
3.3.3 The North Sea Herring Fishery 1981-2001 . . . 120
3.4 Summary and Conclusions . . . 128
References . . . 132

4 Regime Switching in a Stochastic Fishery 135
4.1 Introduction . . . 137
4.2 Model Specification . . . 139
4.3 Numerical Analysis . . . 146
4.3.1 Optimal Switching Curves . . . 149
4.3.2 The Optimal Management Fishery . . . 151
4.3.3 Sensitivity Analysis . . . 154
4.4 Summary and Conclusions . . . 159
References . . . 162

5 Cost Structure and Capacity **165**
5.1 Introduction 167
5.2 The Norwegian Pelagic Fisheries 171
5.3 Empirical Specification and Estimation 176
5.3.1 Empirical Model 177
5.3.2 Measuring Capacity and Capacity Utilisation 181
5.3.3 Estimation Results 183
5.4 Production Structure and Policy Implications 184
5.5 Concluding Remarks 193
References 196

List of Figures

2.1 The Open-access Equilibrium Supply Curve 72
2.2 The Discounted Supply Curve 73
2.3 Equilibrium Supply Curves for the Optimally Managed Pure Schooling Fishery 74
2.4 Equilibrium Supply under Open Access and Optimal Management together with Actual Supply,1981-1996 76
2.5 Equilibrium Stock under Open Access and Optimal Management, and Actual Stock, 1990-2001 82
2.6 Equilibrium Supply under Open Access and Optimal Management, together with Actual Supply and Calculated Equilibrium Supply Based on Actual Stock Level, 1990-2000 . . . 83

3.1 Model 1: Optimal Escapement Level 108
3.2 Model 1: Long Run Optimal Stock and Harvest for Different Prices 110
3.3 Model 1: Open-Access Stock and Catch Dynamics 111
3.4 Model 1: Open-Access Vessel Dynamics 113
3.5 Model 1: Long Run Open-Access Stock and Harvest 114
3.6 Model 2: Optimal Management Stock and Catch Dynamics . 117
3.7 Model 2: Optimal Management Stock and Harvest 118
3.8 Model 2: Open Access Time of Extinction and Long-Run Biomass 119
3.9 Open-Access Dynamics, 1981-2002 122

3.10 Optimal Policies versus Actual Policy, 1981-2002 125
3.11 Sum of Present Value of Revenues 126

4.1 Long-Run Stock Density, No Harvesting 148
4.2 Approximate Switching Curves 150
4.3 Sample Realisations of Price and Stock 152
4.4 Long-Run Stock Density: Optimal Policy and No Harvesting 153
4.5 Approximate Switching Curves: Various Volatility Assumptions 156
4.6 Approximate Switching Curves: Various Intrinsic Growth Rates 157
4.7 Approximate Switching Curves: Various Maximum Harvest Rates 158

List of Tables

2.1 Estimated Growth Functions for North Sea Herring 68
2.2 Estimation Results a More General Growth Function 68
2.3 Prices and Variable Costs, 1998-2000 71
2.4 Equilibrium under Open Access and Optimal Management . 77
2.5 Equilibrium under Open Access and Optimal Management, 1998-2000 79

3.1 Estimates of the Parameters of the Stock-Recruitment Function 102

4.1 Parameter Values 147
4.2 Fishery Characteristics by Maximum Harvest Rate 159

5.1 Observations per Vessel Type per Year 172
5.2 Average Harvest, Value, and Price per Vessel, 1998-2000 . . . 174
5.3 Upper Limits for Capacity and Age Quartiles 176
5.4 Factor Price Indices by Vessel Type, 1998-2000 179
5.5 Output Definitions 184
5.6 Generalised Translog Cost Function, Estimates with Standard Errors 185
5.7 Returns to Scale and Input Price Elasticities 186
5.8 RTS by Vessel Age with Standard Errors 190
5.9 RTS by Vessel Capacity with Standard Errors 190

Introduction

The present essay collection is a doctoral dissertation in partial fulfilment of the requirements for the degree of dr. oecon. at the Norwegian School of Economics and Business Administration (NHH). The dissertation consists of five separate essays of which one is a literature review. The aim of the research papers is to contribute to the understanding of the economics of fisheries management. More specifically, the essays consider what optimal extraction from a biomass is, how the harvest (long-run supply curves) changes with different regulatory regimes, how uncertainty affects extraction policies, the effect of switching costs in an uncertain fishery, and what optimal short-term capacity utilisation for a fishing fleet is. As a case study, the Norwegian pelagic fishery is used through out the dissertation. The purpose of this introduction is to motivate the choice of topics and to put the essays in perspective. As chapter 1 is a literature review, I will only give a brief presentation of some of the relevant literature here. The last part provides an outline of the dissertation.

In his inaugural address at the International Fisheries Exhibition in

London 1883, Thomas Henry Huxley made the following statement (cited in Gordon, 1954):

> "I believe, then, that the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea fisheries, are inexhaustible; that is to say, that nothing we do seriously affects the number of the fish. And any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless."

Huxley was not alone in his opinion of the great sea fisheries being inexhaustible; his views were shared by many, including fisheries biologists as late as in the 1950s. With the collapse of many commercial fisheries, e.g. the North Atlantic herring fisheries in the 1960s and 1970s, it has become evident that regulations of some kind are not anymore useless, but crucial to avoid rent dissipation in commercial fisheries.

Considering the high fishing power of modern fishing fleets, it is beyond doubt that human activity can affect the abundance of fish in the oceans. This however does not explain the rent dissipation that takes place in unregulated fisheries (and for that matter in many regulated fisheries). Fish stocks are considered common property resources and the rent dissipation problem in unregulated fisheries has to do with the difficulties in assigning property rights to fish resources. In his seminal paper, Gordon (1954) identified how the lack of property rights leads to excessive fishing effort and over-exploitation of the resource; a scenario known as "the tragedy of the commons" (Gordon, 1954; Hardin, 1968). A large branch of the fisheries economics literature deals with how fisheries should be regulated to avoid rent dissipation. In the following I give a brief presentation of two strands of the fisheries management literature of particular relevance to the dissertation, namely optimal harvesting of fish and capacity utilisation in fisheries.

To avoid excessive fishing effort and over-exploitation of fish stocks, there is a need to impose regulations in fisheries. Fisheries managers typically attempt to deal with the common property problem by use of input and output controls Munro & Scott (1985). Input controls are imposed to restrict fishing effort. Unless the fishery managers can control all inputs effectively, input controls alone cannot solve the common property problem in the long run as fishing firms will increase harvest effort along non-regulated dimensions. Output controls are imposed to restrict harvest. The most commonly used output control is the harvest quota. A total allowable catch (TAC) can ensure sustainable catches. However, unless fishing firms are given property rights to shares of the TAC, there may be incentives to race for fish. Munro & Scott (1985) identify the problem of excess capacity in regulated fisheries, which they refer to as class II open access.

Homans & Wilen (1997) illustrate how regulated open-access fisheries can have very high excess capacity. In a regulated open-access fishery there is free entry but the fishery is subject to certain regulations, such as restrictions on the choice of fishing gear, fishing area, and season length. The introduction of individual transferable quotas (ITQs), an approach based on assigning property rights to the fish stocks, is a solution which has been proposed to address these problems (see e.g. Grafton, 1996). A well-known example of class II open access and ITQs is the Alaska Pacific halibut fishery. In that fishery the fishing season was shortened to reduce total landings and the fishermen responded by increasing fishing effort to compensate for lost fishing time. This led to a progressive reduction of the fishing season. In 1995, what used to be an annual fishery had been reduced to a fishery with an official season of two days (see Wilen & Homans, 1998, on the history of the Pacific halibut fishery). Individual fishing quotas were introduced in the halibut fishery in 1995, and only a couple of years later, the Alaska halibut season spanned 245 days per year.[1]

The use of input and output controls to restrict harvest raises the question of how to set harvest quotas; what is optimal extraction over time from a fish stock? In order to manage fish stocks well, it is essential for the fishery regulator to have knowledge on what optimal management of the fishery involves in terms of harvest and biomass level. From an economist's perspective, this can be obtained by establishing a bioeconomic model of the fishery and maximising present value of net-benefits from harvesting the resource. With the advent of optimal control theory,

[1]Although the introduction of individual fishing quotas turned out to be a success in the Pacific halibut fishery, the literature also mentions many problems with using individual fishing quotas. See e.g. Copes (1986).

resource economics was extended from static (cf. Gordon, 1954) to a dynamic or capital-theoretic context (e.g. Clark, 1971, 1976; Clark & Munro, 1975).[2] This made it, among many other things, possible to analyse optimal harvesting paths (Clark, 1971).

Soon after the introduction of capital-theory as a tool for resource economists, uncertainty was introduced into bioeconomic models. Uncertainty in bioeconomic models of fisheries was reviewed by Andersen & Sutinen (1984). The uncertainty literature has grown considerably since their paper was published. Chapter 1 seeks to give an overview of some of the main developments in the field since its introduction in the early 1970s. The literature review in chapter 1 also aims at providing a basis for chapters 3 and 4, where harvesting policies are analysed in stochastic frameworks.

Chapter 1 gives a detailed presentation of two fairly general stochastic bioeconomic models, one in continuous time and one in discrete time. These models serve as reference points for other studies that are reviewed. The second part of the chapter provides an overview of some of the achievements and the issues that have been dealt with in stochastic bioeconomic modelling thus far. Several applications are considered. The presented studies serve to exemplify the range of issues that have been analysed by incorporating uncertainty into bioeconomic models.

Market analysis is based on supply and demand. Demand functions and market structure have received substantial attention in the fisheries

[2] On the evolution of modern fisheries economics, see Munro (1992).

economic literature, very little attention has however been given to the supply side in fisheries. The seminal paper by Copes (1970) derives the backward-bending open-access supply curve. With the advent of optimal control theory, Clark (1990) derived the equilibrium supply curve for an optimally managed fishery. The literature contains few empirical studies of fisheries supply curves. Bjørndal (1987) estimated a harvest supply function, but the purpose of his study was to use duality to retrieve the characteristics of the underlying production technology, and the supply function per se was not derived. The purpose of chapters 2 and 3 is to derive and estimate equilibrium supply functions for the North Sea herring fishery, i.e., how does the long-run harvest of North Sea herring change as the price of herring changes? Long-run equilibrium supply curves are derived, estimated, and analysed for different management regimes, both theoretical and actual. This is done both in deterministic (chapter 2) and stochastic (chapter 3) frameworks. The applications represent some of the few empirical analyses of supply curves in the literature.

Chapter 3 extends the analysis in chapter 2 as I go from a deterministic to a stochastic setting. The introduction of uncertainty in the bioeconomic model can have large implications for the optimal harvest policy. While the deterministic case offers useful benchmarks, many sources of uncertainty influence real-world fisheries. Uncertainty is incorporated into the bioeconomic model by multiplicatively adding a stochastic term to the equation explaining stock-recruitment (cf. Reed, 1979). In a stochastic setting there is no long-run equilibrium (or steady state) and feedback policies for the optimally managed fishery must be found, i.e., optimal levels of harvest, stock size or effort as a function of the current state of the fishery. The optimal feedback policy depends on stock level, but also on the price of herring. The optimal management of North Sea herring was analysed by Bjørndal (1987, 1988). His analyses were based on deterministic models of the fishery. Introducing uncertainty into the bioeconomic model, as is done in chapter 3, might also give further insight into the optimal management of North Sea herring.

The expected (or average) long-run supply curves estimated in chapter 3 are very similar to the supply curves estimated in chapter 2. In both chapters I find that different regulations, such as open access or optimal management, can have substantial impact on the supply of North Sea herring, where annual equilibrium supply can vary from zero, if the stock is driven to extinction under open access, to a sustainable annual yield of approximately 700 thousand tonnes under optimal management. The reason for this difference is the effective means of harvesting schooling fish stocks, which makes it economically viable to harvest herring even at very low stock levels.

Chapters 2 and 3 also analyse the actual harvest policy in the fishery from 1981 to 2001. According to chapter 3 the fishery should have remained closed until 1983 under optimal management, which implies that the moratorium was lifted too early. A change in the actual regulatory regime was evident in 1996. The implications of this change is analysed in chapter 2. While quotas seem to have been too high in the first part of the period 1981-2001, the problem in the last part of the period seems to be that the annual harvest was not large enough. This allowed the stock to approach a higher level than what maximised rent.

One might ask why the analysis in chapter 3 was undertaken, if uncertainty did not change any of the conclusions from chapter 2. By only considering the expected long-term supply derived from the stochastic model, the results are very similar to those presented in chapter 2. The introduction of uncertainty does however give some additional insights. Among other things, there are large seasonal fluctuations in long-run stock and harvest (or supply) under optimal management when modelling the fishery in a stochastic setting. Instead of harvesting the expected amount of herring for a given price, harvest is seen to fluctuate from zero in some periods to very high quantities in other periods because of environmental shocks to the biomass growth. The supply curves in chapter 3 are therefore presented as expected supply (or harvest) with confidence interval. When employing the stochastic feedback policies to the North Sea herring fishery 1981-2001, there are very large fluctuations in annual optimal harvest. Price and cost shift from year to year, but the analysis in chapter 3 shows that the environmental fluctuations explain most of the annual variation in optimal harvest.

After having studied a fishery with stochastic stock growth in chapter

3, more complexity is added to the model in chapter 4 through the introduction of uncertainty to yet another dimension of the model, namely the price dimension. The purpose of this chapter is to analyse how uncertainty in stock growth and price influence the optimal harvest of fish. In addition, I want to analyse the consequences of fleet-switching costs in a fishery. Whereas the literature contains numerous studies of the management of natural resources under some kind of uncertainty, most of them only analyse how one source of uncertainty influences the bioeconomic model. Few studies consider the effects on optimal management of several sources of uncertainty that simultaneously affect different parts of the bioeconomic model.

The bioeconomic model developed in chapter 4 use the well-known deterministic, linear-control model presented by Clark & Munro (1975) as a starting point. The solution to the Clark-Munro model is a most rapid approach path (MRAP) to the optimal stock level. When the stock reaches the critical level, harvest is set at some interior value, which maintains the optimal stock level (steady state). I make several extensions to the Clark-Munro model. First, both future price and stock are assumed uncertain as price and stock-recruitment evolve according to known stochastic processes. Second, it is assumed that changing the harvest rate in the fishery is subject to certain switching costs. It seems reasonable to assume that increasing and/or decreasing the harvest rate incurs certain costs. In this setting, I show that the optimal policy can be defined by exit and entry curves in stock-price space. The duality property of the switching curves is due to the combination of switching costs and uncertainty in the model. Numerical methods are used to approximate the solution and to characterise the optimal policy. Simulating the optimal policy over a period of time shows that pulse fishing is the optimal behaviour in this linear-control fishery. To my best knowledge this is the first study of optimal switching curves in a fishery with stochastic stock and price.

The results in chapter 4 give theoretical support for the many cases of pulse fishing found in commercial fisheries. The analysis therefore has implications for many real-world fisheries. Looking at the sensitivity of the results to parameter changes, price and stock volatilities do not affect the switching curves much. The maximum harvest rate of the fishing fleet, on the other hand, strongly affects the optimal entry and exit curves. Furthermore, it turns out that having a larger fishing capacity results in a more stable stock despite the fact that the fleet is pulse fishing. The ability of a big fleet to quickly adjust the stock down to the desired level therefore outweighs the effects on stock variability of pulse fishing with a high capacity (or high maximal harvest rate).

Chapters 2-4 have been dealing with harvesting fish stocks. Thus far however, the implementation of harvest quotas has not been regarded. I have simply assumed the efficient amount of inputs is used to harvest any given quantity of fish. As we know, even if harvest limits are imposed to conserve the fish stock, we are not home free. A lack of property rights will result in a race for shares of the total harvest, where fishermen have incentives to increase their harvesting capacity well above what is necessary to harvest the total allowable catch. This problem of excess capacity is dealt with in chapter 5, where an empirical analysis of capacity utilisation in the Norwegian pelagic fishery is carried out. In this essay it is assumed that the total allowable catch of each species is given and the focus is on how efficient the fishing fleet is in harvesting their given quota.

Excess capacity is a short-run measure as it is self correcting in a well-functioning market. There is excess capacity in a fishery if the potential catch of the current fleet is larger than the current catch (see e.g. Ward et al., 2004). The industry has long claimed that there is a high degree of excess capacity in the Norwegiam pelagic fishing fleet. Despite this, Bjørndal & Gordon (2000) could not find evidence of large returns to scale in their study of the fishery. Using new data that have been made available, I estimate a multi-output generalised translog cost function in order to analyse scale economics and whether there is excess capacity in the Norwegian pelagic fishery. The focus in chapter 5 is on economic definitions of capacity as opposed to physical definitions. A capacity measure suggested by Berndt & Morrison (1981) is used, and capacity output is defined as the output that minimises short run average costs. Increasing returns to scale therefore implies excess capacity, as minimum average cost in a single-output production process corresponds to returns to scale equal to unity. The empirical analysis indicates large returns to scale in every segment of the fishing fleet, implying that there is excess capacity. Cost advantages can be obtained by increasing the quantity caught per vessel. However, with total catch given, I conclude that the number of vessels taking part in the fishery must be reduced to take advantage of scale effects.

Until recently, there have been few incentives to reduce capacity in the Norwegian pelagic fleet. The recent introduction of a unit quota system in the purse seine and trawl fisheries has changed this. Under the unit quota system, the number of assigned (unit) quotas is larger than the number of participating vessels. If a vessel with unit quotas is withdrawn from the fishery, its quotas can be transferred to and used by other vessels. The analysis in chapter 5 suggests that quotas per vessel should be increased considerably to take advantage of scale effects. As the total allowable catch in the fishery is given, increased vessel quotas can only be realised by withdrawing vessels from the fishery. The unit quota system has the potential of making such capacity reduction achievable. It remains to be seen if the incentives provided by the unit quota system are strong enough to reduce the excess capacity in the fishery.

Summing up, the questions analysed in the dissertation covers several topics relevant to the fisheries economics literature. First, extraction of fish from a fish stock is considered under many different assumptions about regulatory regime, uncertainty, cost structure, etc. In this part of the dissertation (chapters 2-4), bioeconomic modelling, optimal control theory and numerical methods (cf. Judd, 1998) are fundamental tools. Second, production structure and capacity utilisation in a fishery is analysed by means of duality theory and econometric methods (chapter 5). The span in topics and methods employed is perhaps large, but the topics have at least one important common feature; they are all related to the management of fish stocks and consequences of suboptimal regulations. The aim of the dissertation is thus to contribute to the understanding of the economics of fisheries management.

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Chapter 1

Uncertainty in Bioeconomic Modelling

Abstract

The paper reviews the large body of literature dealing with uncertainty in bioeconomic modelling of fisheries. The purpose is to provide an overview of some of the main developments in the field since its introduction in the early 1970s. We start by giving a detailed presentation of two fairly general stochastic bioeconomic models, one in continuous time and one in discrete time. These models serve as reference points for other studies we discuss. The purpose of the second part of the paper is to provide an overview of some of the achievements and issues that have been dealt with in stochastic bioeconomic modelling thus far. Several applications are considered. The studies we present serve to exemplify the range of issues that have been analysed by incorporating uncertainty into bioeconomic models.

1.1 Introduction

Uncertainty was introduced in bioeconomic models in the early 1970s and an extensive literature has been generated since that time. The aim of this paper is to review some of the main developments in stochastic bioeconomic modelling. A complete survey of all aspects of the literature is impossible in the space allocated for this paper, and the aim is rather to present a sample of the literature to represent some of the achievements and to exemplify the range of topics analysed by use of stochastic bioeconomic models. For a more detailed survey of the earlier literature, the reader might refer to Andersen & Sutinen (1984).

Walters & Hilborn (1978) list the following three categories of uncertainty in fisheries management: (1) random effects, whose probability distribution can be determined from past experience, (2) parameter uncertainty, and (3) fundamental misunderstanding about variable choice and model form. The various forms of uncertainty along with methods used to analyse them are reviewed in Charles (1998). Most bioeconomic studies focus on the first two classes of uncertainty.

The standard bioeconomic model consists of a biological component, describing change in one or more resource stocks, and an economic part describing net revenue, net benefits or "social welfare". Uncertainty can be added to the model in several ways. The biological component can be made stochastic by allowing for random fluctuations in the stock-growth relationship. In addition, one might assume stock levels are observed with measurement error. Uncertainty can be introduced to the economic component by letting prices, costs, yield-effort relationships etc. fluctuate according to some stochastic process.

The reminder of the paper is organised as follows. In the next section we present two studies of uncertainty in bioeconomic modelling; the first model is in discrete time whereas the second is modelled in continuous time. These models will later serve as references when reviewing other studies. Section 1.2 also gives a brief introduction to basic methods for solving stochastic dynamic optimisation problems. Section 1.3 gives an overview of applications of stochastic bioeconomic modelling. Section 1.4 concludes.

1.2 Stochastic Bioeconomic Models

In the bioeconomic literature we find stochastic models both in discrete time and in continuous time. In this section we present two models, a discrete-time model and a model in continuous time. The models will serve as reference points for the remainder of the paper and they present some basic methods used to solve stochastic dynamic optimisation problems. The often-cited paper by Reed (1979) is presented as a point of reference for discrete-time models. Among the models in continuous-time, we have chosen to present Pindyck (1984) as an example. Conrad (2004) provides a detailed description of both Reed's and Pindyck's models in his review of renewable resource management.

1.2.1 A Discrete-Time Model

Reed (1979) draws on the analyses in Jaquette (1972), Jaquette (1974) and Reed (1974), and the model is used to derive an optimal harvest policy for a fishery. Reed (1979) uses a stochastic stock-recruitment function:

$$X_{t+1} = z_{t+1}G(S_t), \tag{1.1}$$

where X_t, $S_t = X_t - Y_t$, and Y_t is biomass, escapement, and harvest in period t, respectively. z_{t+1} are independent and identically distributed (iid) random variables with mean one and constant variance, observed at the beginning of period $t + 1$. $G(S_t)$ is a growth function. Harvesting from the stock is explained by the Spence production function $Y_t = X_t(1 - e^{-qK_t})$, where K_t represents effort and $q > 0$ is a catchability coefficient.[1] By assuming a constant cost per unit effort (CPUE) of c and a constant price p per unit harvest, net revenues are given by $\pi_t = pY_t - (c/q)[ln(X_t) - ln(S_t)]$. Using the fact that net revenues can be written as an additively separable

[1] Spence (1974) used this production function in his study of blue whales. The Spence production function is a discrete-time analogue to the (continuous-time) Schaefer production function: Let instantaneous harvest during a period be given by the Schaefer function $y(t) = qEx(t)$, where the period's E is fixed. Instantaneous stock change is given by $\dot{x}(t) = -qEx(t)$ and by solving this differential equation we get $x(t) = X_0e^{-qE_t}$. The total harvest in a given period with initial stock X_t can therefore be expressed by $Y_t = X_t(1 - e^{-qE_t})$, i.e., by the Spence production function.

function of X and S, we get the expression $\pi_t = N(X) - N(S)$, where $N(m) = pm - (c/q)ln(m)$. The optimal policy is derived by maximising the expected present value of net revenues

$$\max_{\{S_t\}} E_0 \left[\sum_{t=0}^{T} \rho^t \{N(X_t) - N(S_t)\} \right],$$

subject to (1.1), $0 \leq Y_t \leq X_t$, and X_0 given, where ρ is the discount factor. The maximisation problem is solved using stochastic dynamic programming. The optimal harvest policy is a constant-escapement policy where the optimal escapement level S^* must maximise the equation $W(S) = \rho E_z[N(zG(z))]$. The optimal feedback policy can be expressed as:

$$Y_t = \begin{cases} (X_t - S^*) & if \quad X_t > S^* \\ 0 & if \quad X_t \leq S^* \end{cases}$$

Stock, harvest, and effort will fluctuate over time. Given a statistical distribution for the random variable z, it is possible to find the statistical properties of stock, harvest, etc. analytically or through numerical approximations.

Reed is able to derive the optimal feedback policy analytically because net revenues in his model can be written as an additive separable function of the state and the control variables, i.e., he uses a linear control model. His choice of production function is crucial and a slightly different model specification would have made it impossible to derive a closed form solution. In most stochastic bioeconomic models where net revenues are maximised, it is very difficult (or impossible) to derive closed form solutions and numerical approximations must be used.

1.2.2 A Continuous-Time Model

One of the first bioeconomic studies in continuous time dealing with uncertainty is Ludwig (1979). Ludwig extends the classic, deterministic fishery model of Clark (1976) by including stochastic change in the resource stock. Ludwig's model is similar to Reed (1979) with a linear control relationship and a fixed and exogenous resource price. Also, the optimal feedback policy derived from Ludwig's model is similar to the constant escapement policy derived from the Reed (1979) model. According to Ludwig, one should harvest either at the maximum or the minimum harvest rate depending on the current size of the stock (i.e., a bang-bang approach). Pindyck (1984) extends Ludwig's model by letting price be determined by a downward sloping demand curve. In the following we present Pindyck's model which in turn serves as a reference for other bioeconomic models in continuous time.

In Pindyck (1984) the stock evolves according to

$$dX = [F(X) - Y]\,dt + \sigma(X)dz, \tag{1.2}$$

where $\sigma'(X) > 0$, i.e., the variation in stock growth increases with the size of the stock, $\sigma(0) = 0$, and $dz = \epsilon(t)\sqrt{dt}$ is the increment of a Wiener process. $Y(t)$ is the harvest rate. The stock-growth function $F(X)$ is assumed to be strictly concave with $F(0) = F(K) = 0$, where $K > 0$ is the carrying capacity of the resource in its natural environment.

Let net benefits at instant t be given by

$$U(X,Y) = \int_0^Y p(q)dq - c(X)Y, \tag{1.3}$$

where $p(Y)$ is the downward sloping demand curve, and c(X) is unit cost of harvesting from a stock of size X. $c(X)$ is assumed decreasing and strictly convex, and with $c(0) = \infty$. Pindyck further assumes a competitive resource market, well defined property rights, and risk-neutral firms.

Maximisation of discounted net benefits subject to (1.2) gives the following Hamilton-Jacobi-Bellman (HJB) equation:

$$\delta V(X) = \max_Y \left\{ \int_0^Y p(q)dq - c(X)Y + [F(X) - Y]\,V'(X) + \frac{1}{2}\sigma^2(X)V''(X) \right\}, \tag{1.4}$$

where δ is the discount rate. From the maximal condition $\partial\{\cdot\}/\partial Y = 0$ we have that $p(Y^*) - c(X) = V'(X)$.

Assume stock growth is given by a logistic growth function $F(X) = rX(1 - x/K)$, inverse demand is given by $p = b^2/Y^2$, with $b > 0$, the cost function is $c(X) = c/X^2$, with $c > 0$, and $\sigma(X) = \sigma X$. The HJB equation (1.4) then becomes:

$$\delta V(X) = \max_{Y}\left\{\frac{-b^2}{Y} - \frac{cY}{X^2} + \left[r\left(1-\frac{X}{K}\right) - Y\right]V'(X) + \frac{1}{2}\sigma^2 X^2 V''(X)\right\} \tag{1.5}$$

Using the maximal condition $\partial\{\cdot\}/\partial Y = 0$ we can solve for the optimal harvest rate:

$$Y^* = b\left[\frac{c}{X^2} + V'(X)\right]^{-\frac{1}{2}} \tag{1.6}$$

Substituting for harvest rate from equation (1.6) into equation (1.5) gives us the following second-order differential equation:

$$\delta V(X) = -2b\left(\frac{c}{X^2} + V'(X)\right)^{\frac{1}{2}} + rX\left(1-\frac{X}{K}\right)V'(X) + \frac{1}{2}\sigma^2 X^2 V''(X) \tag{1.7}$$

In general it can be very difficult if not impossible to find a closed form solution to this kind of problem. In this specific case, however, Pindyck is able to solve equation (1.7) and obtain an explicit solution for the value function $V(X)$. The solution is:

$$V(X) = -\frac{\phi}{X} - \frac{\phi r}{\delta K}, \tag{1.8}$$

where

$$\phi = \frac{2b^2 + 2b\left[b^2 + c\left(r + \delta - \sigma^2\right)^2\right]^{\frac{1}{2}}}{\left(r + \delta - \sigma^2\right)^2}$$

Taking the first derivative of $V(X)$ and inserting into equation (1.6), the optimal harvest rule can be expressed as

$$Y^*(X) = b\,(\theta + c)^{-\frac{1}{2}}\,X,$$

and we see that the optimal harvest rate is linear in stock size. By applying the Kolmogorov forward equation, the steady-state probability distribution for stock can be found.[2] Pindyck (1984) also provides two other examples where he specifies bioeconomic models and derives closed-form solutions for the optimal harvest policies. These examples, along with the one presented above, demonstrate, among other things, how an increase in $\sigma(X)$ can increase, decrease, or leave harvest rates unchanged.

1.3 Applications in Bioeconomics

There has been an extensive development in the application of uncertainty in bioeconomic models. It is impossible to review all the accomplishments in this literature but in the following we try to give an overview of some of the issues that have been dealt with. The topics and papers discussed in this section are not meant to give a comprehensive overview of the literature. The purpose is rather to exemplify the range of issues that have been analysed by use of stochastic bioeconomic modelling.

[2]See Dixit & Pindyck (1994) for a presentation of the Kolmogorov forward equation and an excellent introduction to stochastic-diffusion optimal control theory.

1.3.1 Optimal Harvest from a Fish Stock

In the deterministic setting the analysis of optimal harvesting typically involves finding the optimal steady-state harvest and biomass level along with the corresponding optimal approach path from the initial stock level (see e.g. Clark & Munro, 1975; Clark, 1976).[3] In a stochastic fishery there is no steady state. The system is randomly changing and as a result optimal harvest must be specified for every state that can possible occur. Instead of deriving optimal steady-state harvest, the optimal harvest policy, i.e., harvest as a function of state, must be found.

In the papers by Reed (1979) and Pindyck (1984) presented in section 1.2, stochastic optimisation was used to derive optimal harvest policies. A number of papers extend these models and in the following some of them are discussed.

Lewis (1981) develops a discrete time, Markov model of a fishery. Whereas Reed (1979) introduced uncertainty to the stock-growth relationship, Lewis analyses the case of uncertain catchability. Lewis further assumes biomass can be described by a finite number of states represented by possible stock sizes. Population dynamics in Lewis (1981) are given by $X_{t+1} = X_t + G(X_t) - \eta_t a X_t K_t$, where $G(X_t)$ is a logistic growth function, and $\eta_t a X_t K_t$ is a production function giving catch in period t. Uncertainty is

[3]It is common to make the assumptions that (i) stock growth is concave in stock and (ii) the objective function is concave in harvest. If assumption (ii) is relaxed, continuous harvesting strategies may be outperformed by other harvesting policies (see e.g. Lewis & Schmalensee, 1977).

introduced by letting η_t be a uniformly distributed random variable with mean one. Markov transition probabilities of moving from one state to another is calculated and used to obtain the optimal solution through dynamic programming. The optimal strategy is seen to be a function of stock size (state), which is revealed to the fishery manager each period prior to decision making. Optimal strategies are derived for three different cost specifications: zero costs, and increasing and decreasing marginal costs of effort. While a deterministic analysis is found to provide a good approximation to stochastic analysis in the case of increasing marginal costs, deterministic harvest rules are poor substitutes for the optimal stochastic strategies when costs are decreasing in effort or zero.

Spulber (1982) extends the Reed (1979) model by letting the environmental disturbances follow a general Markov process, i.e., $z_{t+1} = \phi(\cdot|z_t)$, where $\phi(\cdot)$ is a probability distribution, and by assuming, like Reed (1974), that fishing firms face a fixed set-up cost of harvesting L. Spulber proves that the optimal harvest policy in this case is given by:

$$Y_t = \begin{cases} (X_t - S(z_t)) & if \quad X_t > S(z_t) \\ 0 & if \quad X_t \leq S(z_t) \end{cases}$$

where $S(z) \leq s(z)$ ($S(z) = s(z)$ if $L = 0$). The optimal harvest rule is similar to that of Reed (1979) with some important distinctions. First, optimal escapement depends on the expected stock-recruitment as given by the value of the random variable z. Second, the the net revenues from harvesting must cover the setup cost and if harvests cannot be large enough to cover setup costs, it is optimal for the fishing fleet to be inactive. For this reason $[S(z) - s(z)]$ increases with L from zero when $L = 0$. The model reduces to the Reed model if z_{t+1} are iid and $L = 0$. Spulber (1982) also evaluates the stability of the harvest policy and finds that there exists a stable equilibrium probability distribution for the stock, independent of the previous stock and the environmental shock. He shows that pulse-fishing policies are optimal within this framework.

In the Reed (1979) model, stock-recruitment is stochastic. Shocks are assumed to occur after harvesting in one period and before next period's recruitment. Before deciding how much to harvest, one knows the exact size of the stock with certainty. In most real-world fisheries, estimates of stock size are not perfect. Clark & Kirkwood (1986) deal with this by modelling a fishery using a framework similar to Reed's but where the uncertainty is revealed after the harvest level has been determined. They thus assume that X_{t+1} in equation (1.1) is a random variable with a given probability distribution dependent upon the known escapement level S_t. Using this specification, Clark and Kirkwood show that the optimal harvest policy is not a constant escapement policy as in the original Reed model. The optimal policy in Clark and Kirkwood's model can however only be approximated numerically.

Sandal & Steinshamn (1997) extend the Pindyck (1984) model by assuming nonlinearity in the control variable Y. Instantaneous net revenues are then given by $\Pi(X,Y) = p(Y)Y - c(X,Y)$, where $p(Y)$ is the linear downward sloping demand curve and $c(X,Y)$ is a cost function increasing in Y. As in Pindyck, Sandal and Steinshamn seek to find the harvest rate that maximises the present value of net revenues subject to the dynamic constraint given by equation (1.2). By applying perturbation methods they derive approximate expressions for optimal feedback policies, i.e., harvest rate as a function of stock size, under various assumptions.

Many other papers analyse optimal harvesting of a stock with stochastic stock growth. Lungu & Øksendal (1997) analyse what harvest policy maximises discounted harvest from a stock evolving according to the stochastic logistic equation $dX = X(1 - \frac{X}{K})(rdt + \sigma dz) - Y$, which is slightly different from the stock dynamics equation (1.2) of Pindyck (1984). They show that optimal harvesting in this case is a constant escapement policy. By maximising discouted harvest they ignore harvesting costs. See e.g. Alvarez & Shepp (1998), Alvarez (2001), and Framstad (2003) for extensions of the analysis in Lungu & Øksendal (1997) and for alternative model specifications.

Sethi et al. (2005) develop a discrete model with three sources of uncertainty incorporated: growth, stock measurement, and harvest quota implementation. Stochastic stock growth follows Reed (1979) and is given by equation (1.1). Stock measurement and actual harvest are given by $X_t^m = z_t^m X_t$ and $Y_t = \min(X_t, z_t^i Y_t^q)$, respectively, where z_t^m and z_t^i are random variables, and Y_t^q is the harvest quota. The authors are able to numerically approximate the optimal policy of the problem of maximising expected present value of the fishery over an infinite horizon. They analyse how the optimal policy change when one of the uncertainty sources are high while the others are low. If the growth or implementation uncertainties are high, the optimal policies are not qualitatively different from Reed's constant escapement policy. With high measurement uncertainty however, Sethi et al. (2005) find that the optimal policy changes significantly. Compared to the optimal constant escapement policy (Reed, 1979), the optimal policy is seen to lower the risk of extinction.

Optimal harvesting has also been studied under price uncertainty. One example is Hanson & Ryan (1998) who study optimal harvesting from a fish stock subject to price and stock uncertainty. They find, not surprisingly, that price fluctuations have a big impact on the value of the fishery, but only a modest impact on the optimal harvest policy.

Costello et al. (1998) and Costello et al. (2001) analyse optimal harvesting under environmental stock uncertainty and study the value of environmental prediction and how prediction changes optimal harvest. The studies find the effect on current harvest policy (and forecast value) of predictions beyond a one-year forecast to be modest or non-existent.

1.3.2 Relative Efficiency of Management Instruments

The question of taxes versus quotas in renewable resource management has been considered by several authors throughout the years. In a deterministic setting the two are equally good, but this might no longer be the case when uncertainty is introduced to the model. The efficiency of other management instruments has also been analysed and compared. In the following we review some of the literature dealing with the relative effect of fisheries management instruments.

The classic paper on "prices vs. quantities" is Weitzman (1974). Koenig (1984a,b) follows along the lines of Weitzman (1974) and evaluates benefits and costs associated with different management instruments in a stochastic discrete-time model. He makes several simplifying assumptions to be able to solve the dynamic programming problem, including the assumption of a linear growth relationship: $X_{t+1} = \phi_0 + \phi_1 (X_t - Y_t) + z_t$, where ϕ_0 and ϕ_1 are constants, and z_t is a zero-mean random variable. Both cost and benefit functions are quadratic and uncertainty is included by adding random disturbances to the linear terms. Koenig's cost and benefit functions are respectively

$$\begin{aligned} C(X_t, Y_t) &= (c_0 + \eta_t)Y_t + \frac{1}{2}c_1 Y_t^2 - c_2 X_t Y_t \\ \pi(Y_t) &= (b_0 + \gamma_t)Y_t - \frac{1}{2}b_1 Y_t^2, \end{aligned}$$

where b_0, b_1, c_0, c_1, and c_2 are positive constants, and η_t and γ_t are random variables with mean zero. If there is no measurement error in the stock estimates ($z = 0$), Koenig shows that taxes are at least as efficient as quotas and strictly better in the presence of demand or supply uncertainty. If stock size is observable only with error, harvest quotas can outperform landing taxes depending on the relative elasticities of market supply and demand (Koenig, 1984b). In a recent paper, Jensen & Vestergaard (2003) discuss conditions for applying the results of Weitzman (1974) to fisheries.

Androkovich & Stollery (1991) use a model very similar to Koenig's but with a slightly different treatment of risk. While Koenig assumes harvest decisions are made with full information whereas tax rates are set with incomplete information, Androkovich & Stollery (1991) assume that both decisions regarding tax rates and whether to harvest are taken before the realisation of the random variables. Using this slightly different model formulation they find that a landing tax is always superior to harvest quotas.

Yet another analysis of taxes versus quotas is Anderson (1986). His approach differs from the studies presented above in that he combines discrete-time and continuous-time bioeconomic models. Regulatory decisions are made at discrete time steps, whereas fishing and stock dynamics are modelled in continuous time. Anderson (1986) finds that neither taxes nor quotas are generally superior; the optimal policy depends on the characteristics of the specific fishery.

Mirman & Spulber (1985) analyse fishery regulations under harvest uncertainty in a discrete model. Compared to the Reed (1979) model there are several similarities, but Mirman and Spulber make some additional assumptions. As in the Reed model, the fishery regulator has perfect information on the size of the stock and makes regulatory decisions after observing last period's growth but before knowing next period's growth. In contrast to the Reed model, Mirman and Spulber assume the individual fishing firm does not necessarily know the current fish stock. The yield-effort relationship is therefore uncertain. They show that with yield-effort uncertainty, both taxes on landings and vessel quotas might have unintended and unfortunate effects. A landings tax can be used to regulate effort optimally but with harvest levels exceeding optimal harvest, whereas a vessel quota limits harvest to the optimal level but with excessive effort. Mirman and Spulber suggest applying taxes and quotas together and they show how this combination induces the fishing firms to choose optimal effort and optimal harvest levels.

In a recent paper, Weitzman (2002) specifies a discrete-time model similar to Clark & Kirkwood (1986) by assuming regulatory decisions are made before the recruitment level is known. He uses his model to compare two management instruments, a unit landing fee and catch quotas, and he draws the conclusion that the landing fee is always superior to catch quotas. His conclusion is therefore the same as that of Androkovich & Stollery (1991). The conclusion is perhaps not surprising given that Weitzman's model includes environmental uncertainty but no economic uncertainty and therefore favours the landing tax. Weitzman's analysis, or perhaps rather his conclusions, has triggered renewed interest in studies of landings taxes versus harvest quotas (e.g. Hannesson & Kennedy, 2005).

We have seen several examples of stochastic bioeconomic models being used to evaluate the relative performance of landings taxes to catch quotas. These studies do however not give an unambiguous answer. To prove analytically that one instrument is superior to the other, one has to make several rather restrictive assumptions. The work on the subject has therefore given us conditions for when an instrument is superior to the other rather than a general conclusion of superiority.

The relative efficiency of other management instruments has also been studied in the literature. Hannesson & Steinshamn (1991) use a one-period model to compare a constant harvest rule to a constant effort rule when faced with a stochastically varying stock. If the revenue function is concave, a constant catch quota equal to the expected harvest of a constant effort rule is shown to yield a higher average income than the constant effort rule. If harvest is a function of stock and effort and concave with respect to stock size, a constant catch rule gives higher average costs. Hannesson and Steinshamn therefore conclude that neither rule is superior; it depends on the sensitivity of CPUE to changes in stock. Quiggin (1992) extends Hannesson and Steinshamn's analysis by deriving conditions for superiority of constant effort rules to constant catch rules. As Hannesson & Steinshamn (1991), Quiggin (1992) uses a one-period model in his analysis.

Danielsson (2002) further extends the analysis of relative efficiency of catch quotas to effort quotas by including stock dynamics with uncertain stock growth and stochastic variations in the CPUE. By including stock dynamics, the effect of the present period's harvest on next period's stock size is taken into account. Danielsson's model is to some extent related to the Reed (1979) model but with some exceptions. Instead of equation (1.1) stock dynamics are explained by $X_{t+1} = S_t + f(X_t, \epsilon_t)$, where ϵ_t is a random variable representing uncertainty in stock growth. Danielsson uses a production function of the form $Y_t = H(K_t, X_t + f(X_t, \epsilon_t), \eta_t)$, where η_t is a random variable reflecting variations in CPUE independent of stock size. In addition, Danielsson allows for measurement error in stock estimates by letting $X_t = m\left(X_t^m, \theta_t\right)$, where X_t^m is measured stock size, and θ_t is a random variable possibly correlated with η_t. Maximised expected present value of net benefits from the fishery, where benefits (utility or profits) are expressed as a function of stock size and fishing effort, are derived both for catch quotas and for effort quotas. Based on this, Danielsson derives sufficient conditions for situations when management with catch quotas is superior to management with effort quotas and *vice versa*.

Herrera (2005) analyse the relative efficiency of different management instruments focusing on bycatch and discarding. He develops a two-stock model of an input regulated fishery with stochastic bycatch. He evaluates the relative efficiency of four regimes: price instruments, trip-based value and quantity limits, and no output regulations. He concludes that price instruments (taxes or subsidies) are more efficient than the trip-based quotas he analyse, namely value and quantity limits. Comparing trip-based quotas, value limits are found to give better results than quantity limits, as they eliminate some of the incentives to discard.

Marine protected areas have recently received widespread attention as a management instrument that recognises the importance of spatial processes in the bioeconomic system. Marine reserves and spatial modelling of fish stocks will be discussed in section 1.3.5.

1.3.3 Management of Shared Fish Stocks

Stochastic modelling can contribute to the understanding of game theoretical aspects of the management of shared fish stocks. Information or believes on the sources and magnitude of variation may vary between the players. It may also be in the players' interest to conceal information from one another. Uncertainty might therefore, *inter alia*, destabilise otherwise satisfactory sharing agreements. An important part of the bioeconomics literature deals with the management of transboundary fish stocks. There are however very few studies that incorporate uncertainty. One exception is the application of stochastic game theory to the management of fisheries by Kaitala (1993). Another exception is the recent study by Laukkanen (2003), who establishes a model of a sequential fishery based on the Reed (1979) model. Laukkanen's model is as follows. A fish stock is assumed to migrate between two areas, a feeding area and a breeding area. Two agents harvest the stock. Agent 2 operates in the breeding area and his initial stock is the observed escapement from the feeding area where Agent 1 operates. Agent 2 determines his harvest level based on the observed initial stock level in the breeding area. Before the stock migrates back to the feeding area, the stock grows stochastically according to equation (1.1). Agent 1 observes the initial stock migrating to the feeding area and decides how much to harvest. What he does not know is the escapement from the breeding area, i.e., the stock left unharvested by agent 2 before recruitment. In contrast, agent 2 has full information on agent 1's escapement level. Laukkanen assumes risk neutral agents who seek to maximise profits. Harvest is explained by the Schaefer production function ($Y = qEX$). Both cooperative and non-cooperative harvest policies are analysed within this framework and Laukkanen is able to derive conditions under which cooperation is sustained as a self-enforcing equilibrium.

Considering that much attention has been focussed on international management of shared fish stocks in the fisheries economics literature, it is somewhat surprising that so few have incorporated uncertainty in their models.

1.3.4 The Risk of Biomass Collapse

One strand of the literature deals with the risk of stock collapse. Similar analyses of the effects of catastrophic risks can be found in the forestry literature, e.g. Reed (1984) who considers the effects of the risk of fire on the optimal rotation period of a strand of trees. Returning to the bioeconomic literature, Clemhout & Wan (1985) study a renewable resource under the random threat of extinction. The model is in continuous time and the instantaneous probability of extinction is decreasing in stock size. Clemhout and Wan model individual fishing firms' harvesting from the stock in a game theoretical framework and study both cooperative and non-cooperative stationary solutions. A stationary solution is defined as a situation with constant stock and harvest rates until the time of sudden resource extinction. Stationary solutions are derived analytically and show that the stationary cooperative stock is larger than the stationary non-cooperative stock. Consequently, cooperation increases the survival prospect of the resource.

Amundsen & Bjørndal (1999) develop a model where the biomass collapse is due to exogenous factors. This is similar to what is referred to as 'environmental collapse' in an earlier study by Johnston & Sutinen (1996). The probability of collapse, provided that it has not already occurred, is assumed constant as time goes by and the size of the collapse is assumed to be a known function of the stock size prior to collapse. Amundsen and Bjørndal find that the optimal stock can be above, equal to, or below the no-collapse stock, depending on the size of the collapse and the failure rate. When harvest costs and the size of the collapse are independent of stock size, it is shown that the optimal pre-collapse stock is larger than the optimal no-collapse stock. If, instead, the collapse is a given percentage of the total stock, the optimal stock is always below the optimal no-collapse stock.

Bulte & van Kooten (2001) develop a bioeconomic model with stochastic stock growth and risk of downward shifts in stock caused by catastrophes, which are modelled as a Poisson jump process. They use their model to analyse the concept of minimum viable population size.

Several studies analyse sustainable harvesting where the risk of extinction typically is minimised given certain conditions, e.g. maximisation of discounted rents or annual yields. Ludwig (1995) models stock dynamics in a similar manner to Bulte & van Kooten (2001) and analyses the concept of sustainability. In Ludwig (1998) he continues the work on stocks under the threat of collapse, this time focusing on optimal management.[4]

1.3.5 Spatial Bioeconomic Models and Marine Reserves

Lately, spatial bioeconomic models have been given increased attention by fisheries economists and others, and the focus has in particular been on the study of marine reserves or marine protected areas. Deterministic models of marine reserves have shown that they, if anything, reduce the value of fisheries when harvest can be set optimally. Also stochastic bioeconomic models have been used to analyse the effects of marine reserves. One of the early rationales for marine reserves was the view by Lauck et al. (1998) that marine fisheries confront managers with "irreducible uncertainty;" i.e., uncertainty that cannot be further reduced with more information or predictive models, and that in the face of irreducible uncertainty, no-fishing

[4]See also the work by Engen, Lande and Sæther on sustainable harvesting of stochastic stocks under the risk of resource collapse (Lande et al., 1994, 1995, 1997; Engen et al., 1997; Sæther et al., 1996).

zones might be the best strategy. The common opinion in the fisheries economics literature is that protecting the source by establishing a marine reserve is effective in the case of sink-source systems (for a definition see e.g. Sanchirico & Wilen, 1999), where young individuals are found in one area ('source') before migrating to other areas ('sinks'). In most other cases however, no unambiguous conclusions have been reached.

Sumaila (1998) develops a discrete time, bioeconomic model of the Barents Sea cod fishery and analyses the optimal size of a marine reserve when a large shock is introduced to the system. The analysis is done by adding the occurrence of a large negative shock in stock recruitment from the fishing area, to an otherwise deterministic model. Seeking to maximise discounted net revenues from the fishery, numerical methods are used to approximate the solution of the problem. In Sumaila (2002), the work is extended by assuming that two vessel groups participate in the fishery. It is analysed how marine reserves affects the payoffs of the two players under cooperative and competitive management. In both studies, Sumaila concludes that marine reserves represent effective protection against dramatic, negative shocks. This is in line with Lauck et al. (1998), who also consider irreducible or true uncertainty.

Several authors suggest marine reserves to secure the biomass at a sustainable level in the presence of harvest uncertainty (e.g. Mangel, 1998; Doyen & Béné, 2003).

Hannesson (2002) develops a continuous-time model of two patchy populations, neither being a source or a sink. The growth equation (1.2) is modified to describe growth in two interdependent sub-stocks. If the fishery is unregulated (open access), closing off one area is seen to reduce the variability of the catch and increase the total population. However, Hannesson finds no increase in expected rents from protecting one sub-population. While Hannesson considers the effects of marine reserves with open access elsewhere, Conrad (1999) analyses the effects of marine reserves under the assumption of a total allowable catch given by a linear policy in the open area (i.e., total allowable catch is a constant share of the stock size in the open area). Conrad's model is in discrete time and incorporates uncertainty in a manner similar to Reed (1979). His analysis shows how the variability in biomass is reduced when an area is closed off.

Grafton et al. (2004) develop a model of an uncertain fishery, where two sources of uncertainty are incorporated. Environmental variability is modelled as a Wiener process and the possibility of a negative shock is included as a Poisson process. The model is used to analyse the value of a marine reserve when harvesting is optimal. Net economic return is maximised over harvest and reserve size. They find that marine reserves generate values that cannot be obtained through optimal choice of harvest and effort levels alone.[5]

Bulte & van Kooten (1999) analyse optimal harvesting of a stock con-

[5]See Grafton & Kompas (2005) for a presentation of this and other studies on marine reserves and uncertainty.

sisting of two local subpopulations. Stock growth is stochastic in both subpopulations and the analysis is done in a continuous-time framework similar to Hannesson (2002). Instead of protecting one area, they consider the possibility of managing the two subpopulations independently. Using stochastic optimisation, they derive expressions for optimal harvest in each area and find that total harvest might increase or decrease compared to total harvest when treating the subpopulations as one stock. By managing the subpopulations independently, the fishery manager can take advantage of migration by choosing local harvest rates and thereby increase total harvest. Furthermore, if stock-growth in the two subpopulations is dependent, the manager can hedge against risk.

In a recent work by Costello & Polasky (2005), a spatial, discrete time model of a fishery is developed, in which four sources of uncertainty is incorporated. All sources of uncertainty are biological: (i) stochastic spatial dispersal, and random environmental shocks to (ii) production of young, (iii) survival of adults, and to (iv) survival of settlers. Using dynamic programming they manage to derive an interior solution to the fishery's rent maximisation problem. The existence of an interior solution implies that the harvest rate in each fishing area is positive and that no area should be closed. The problem is found to have an interior solution if the stock size in every patch is sufficiently large. The paper also considers conditions for corner solutions, which mean that an area closure is optimal, and concludes that marine reserves can be optimal "under a number of different, and realistic, bioeconomic conditions."

Whereas most studies discussed thus far have been optimisation analyses, there is a significant literature on behavioural models of fisheries. Discrete choice models have been used to predict fisherman behaviour and an often-sited reference in the fisheries literature is Bockstael & Opaluch (1983), who analyse seasonal gear choice and target species. The key element of discrete choice models is that individual choice is driven by utility, where utility is assumed to consist of a deterministic part and a random component. The models further allows for heterogeneity among individuals. Discrete choice or random utility modelling can be used to describe spatial behaviour, e.g. choice of fishing ground, and is therefore very suitable for analysis of marine reserves as a management instrument or spatial management of fish stocks in general.

Smith & Wilen (2003) link a spatial behavioural model to a biological model of the northern California red sea urchin fishery and analyse how rent will be spatially dissipated by mobile divers in the fishery. The spatial behaviour of the divers is modelled and estimated in a repeated nested logit framework, where daily discrete participation and choice of fishing location are modelled jointly. The estimated model shows that fishermen adjust to spatial differences in expected returns. Based on the nested logit estimates, Smith and Wilen calculate cross-revenue elasticities, which show how changes in expected revenues in one fishing area, or "patch," affects effort employed per area. The biological model represents the sea urchin population as a metapopulation consisting of eleven fishing areas linked with a dispersal matrix. The implications of spatial closures are analysed by simulating the integrated model with and without a closure of one of the patches. The authors find that accounting for fishermen's spatial behaviour offsets the harvest gains from marine reserves in the sea urchin fishery and concludes that optimistic results obtained about reserves may be due to simplifying assumptions that ignore economic behaviour. In Smith & Wilen (2004) they extend the analysis by letting the choice of fisher home port be endogenous and thereby allowing for simulation of both short and long run diver behaviour. Although allowing for port switching has some new implications for the predictions made, the main conclusion remains the same, namely that traditional analysis of marine reserves as a management instrument might be biased in favour of reserves because of oversimplified assumptions made about fisherman behaviour.

1.3.6 Other Issues

The literature deals with several issues beyond those covered in this review. A number of papers examine uncertainty in multi-cohort and multi-species models (e.g. Mendelssohn, 1978, 1980; Spulber, 1983; Reed, 1983; Kennedy, 1989). These models are similar to the single-cohort, single-species models discussed above although the inclusion of additional cohorts and/or species adds to the complexity of the models.

Extensive research has been done on the issue of investment in capacity in the fishing fleet. An often-sited reference on this is Charles (1983) who analyses optimal fleet investment in a stochastic framework. He models change in biomass in a similar manner to Reed (1979). In addition, the capital stock (fishing fleet capacity) is assumed to deteriorate over time and investments, assumed irreversible, are therefore needed if the fishing effort is to be kept up. Using dynamic optimisation, Charles determines optimal policy functions for both fleet investment and stock escapement. Numerical approximations are used to find the optimal policies.

The literature on other natural resources contains many papers related to bioeconomic modelling. There is, for instance, an extensive literature on real options and optimal stopping rules (see e.g. Clarke & Reed, 1990, for a review), a topic that has not been discussed here but, nevertheless, can be applied to bioeconomic models.

1.4 Concluding Remarks

In this paper, we have tried to provide an overview of some of the development in stochastic bioeconomic modelling since the introduction in the early 1970s. We live in a stochastic world and have to deal with inaccurate data and unknown external disturbances in addition to the fundamental uncertainty of the future, etc. To deal with this, uncertainty has been incorporated into bioeconomic models to do normative studies, to analyse industry behaviour, and to evaluate alternative management policies.

The methods used in solving stochastic optimisation problems in resource management have changed since the introduction. In the beginning, the main focus was on deriving analytic solutions. Gradually, and perhaps as a result of increased computer power, the use of dynamic programming and numerical methods has increased. With the powerful computers of today, numerical methods can be used to approximate solutions to fairly complex problems - problems that might have been considered unsolvable just a few years ago.

We have seen how incorporating uncertainty into bioeconomic models can make the models more realistic, provide additional insights, present new problems, and suggest solutions that would not appear from a deterministic analysis. However, the introduction of uncertainty to the model might not be worthwhile although there are underlying random processes influencing the system. If stochastic analysis does not change the implications significantly, one should consider whether it is possible to keep the analysis within a more straightforward deterministic setting, as the incorporation of uncertainty comes at the cost of increased complexity.

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Chapter 2

Supply Functions for North Sea Herring[1]

[1]Co-authored with Trond Bjørndal. A version of this chapter was published in Marine Resource Economics 18(4), pp. 345-361, 2003.

Abstract

A continuous time, bioeconomic model is developed and used to derive supply curves for the open-access and the optimally managed fisheries. Supply curves are estimated based on data for the North Sea herring fishery. Different regulatory regimes in the fishery over the past two decades, both actual and theoretical, are evaluated with respect to effects on supply, stock level, and fishing effort. The results indicate that different regulations can have a substantial impact on the supply of North Sea herring. It is argued that the annual equilibrium supply can vary from zero in case the stock is driven to extinction under open access, to a sustainable annual yield of 690-700,000 tonnes.

2.1 Introduction

Market analysis is based on supply and demand. While demand functions and market structure receive substantial attention in the fisheries economic literature, very little attention is given to the supply side in fisheries. The backward-bending open-access supply curve was derived in the seminal paper by Copes (1970). With the advent of optimal control theory, Clark (1990) derived the equilibrium supply curve for an optimally managed fishery. However, the literature contains few, if any, empirical studies of fisheries supply curves. Bjørndal (1987) estimated a harvest supply function, but the purpose of his study was to use duality to retrieve the characteristics of the underlying production technology, and the supply function *per se* was not derived.

The purpose of this paper is to derive and estimate supply functions for the North Sea herring fishery. A bioeconomic model will be developed and used to derive supply curves for the open-access regime and the optimally managed fishery. These supply curves are then empirically estimated based on data for the fishery. Thus, the paper represents an empirical application of fisheries supply curves under different regulatory regimes.

With the exception of Copes (1970) and Clark (1990), supply functions for fish have received little attention in the literature. This is strange for a number of reasons. In fisheries, as in other sectors of the economy, observed price and quantity figures will be a result of the interaction between supply and demand, as well as government regulations. In such a context, it is important to identify and attempt to quantify the impact of the supply side.

A possible reason for this neglect of the supply side is that, in most bioeconomic models, price is assumed to be fixed. Often, this assumption is made to simplify an analysis of optimal resource management. In our analysis, we want to analyse and quantify how the supply of fish varies with price under different assumptions. Knowledge about the supply function is important with respect to analysis of the fishery under optimal management, open access, and other regulatory regimes. From the perspective of market analysis, knowledge about the supply function is essential. Furthermore, it may help explain the past development of a fishery like the North Sea herring.

In the next section, the herring fishery is presented, a bioeconomic model for the fishery is developed, and equilibrium supply curves are derived. The derived supply curves will be estimated in section 2.3. Section 2.4 contains an analysis of different regulatory regimes in the North Sea herring fishery over the past two decades. The paper is summarised in the final section.

2.2 The Bioeconomic Model

2.2.1 The Herring Fishery

The North Sea autumn spawning herring (*Clupea harengus*) is a pelagic stock that lives on plankton. The stock consists of three spawning stocks with different spawning grounds: the northern, central, and southern North Sea.

Herring of the central and northern populations spawn in August and September in the western North Sea. After spawning, the herring migrate eastwards to spend the winter in the Norwegian Trench. In spring, the fish migrate north along the Norwegian Trench and then west towards Shetland. In May-June, the feeding starts in the northern part of the North Sea. The southern population spawn in December and January in the eastern English Channel. After spending the winter in the southern part of the North Sea, the herring migrate directly to the feeding grounds in the central and northern North Sea. It is normal to treat the three stocks as one because they mix on the feeding grounds, rendering it impossible to distinguish between catches from the different stocks. The herring fishery takes place primarily in the central and northern North Sea during May to September.

The North Sea herring stock was severely depleted in the 1960s and 1970s due to overfishing under an open-access regime combined with the development of very effective fish finding technology (Bjørndal, 1988).

In 1977, the fishery was closed to allow the stock to recover. Since the moratorium was lifted, regulations have been in effect. However, in the mid-1990s the stock once again was below safe biological limits, and in 1996 the total quota was reduced to save the stock from collapse. To rebuild the stock, the quotas have been relatively small since 1996. Recent stock estimates show that it has been rebuilt above the level that guarantees good recruitment (ICES, 2002a).

After the introduction of extended fisheries jurisdiction (EFJ), the North Sea herring has been considered a common resource between Norway and the European Union (EU). Management decisions are therefore agreed upon by Norway and the EU. In December 1997, the parties agreed on a management scheme for the stock, the EU-Norway agreement, specifying stock objectives and how to set catch quotas (Anon., 2001). This agreement has been in force since 1 January 1998. According to the EU-Norway agreement, the total quota for the directed fishery shall be allocated between the two parties with 29% to Norway and 71% to the EU. In addition, the EU gets the entire bycatch quota.[2]

2.2.2 The Bioeconomic Model

The biomass of a fish stock changes over time due to recruitment, natural growth, natural mortality, and harvesting. This can be explained by the

[2]See Bjørndal & Lindroos (2004) on the sharing of the resource between Norway and the EU.

following equation:

$$\dot{X} = F(X) - H(\cdot), \tag{2.1}$$

where $X = X(t)$ is the total biomass at time t, $F(X)$ is natural growth of the biomass, and $H(\cdot)$ is a production function explaining total catch at time t. The natural growth of the biomass will be explained by the logistic growth function

$$F(X) = rX\left(1 - \frac{X}{L}\right), \tag{2.2}$$

where r is the intrinsic growth rate and L is the carrying capacity of the environment.

Harvest at time t (or harvest rate) is given by the following Cobb-Douglas production function:

$$Y(t) = H(K, X) = aK^bX^g, \tag{2.3}$$

where $K = K(t)$ is fishing effort at time t. According to Bjørndal & Conrad (1987), the number of participating vessels may be an appropriate measure of effort, an assumption that will be made in this study.

The standard Schaefer production function is a special case of equation (2.3), where $b = g = 1$. The schooling behaviour of the herring has permitted the development of very effective means of harvesting. With modern fish finding equipment, harvesting can be viable even at very low stock levels. For this reason, we expect $1 > g \geq 0$ for herring. The Cobb-Douglas production function describes a "pure" schooling fishery where catch is independent of stock when $g = 0$ (Bjørndal, 1988).

We assume the cost per unit effort to be constant. Under this assumption, we can write the cost function as:

$$C(X, Y) = cK = c\left(\frac{Y}{aX^g}\right)^{\frac{1}{b}}, \tag{2.4}$$

where c is the variable cost per vessel per fishing season. The variable cost will not include costs associated with the crew, because crew remuneration represents a constant share of the vessel's revenues. We will therefore adjust the income by a factor that represents the boat owner's share. This leaves us with the boat owner's share of both prices and variable costs.

We define industry profit as

$$\pi(t) = pH(K, X) - cK = pY - C(X, Y), \tag{2.5}$$

where p is unit price of harvest. The industry profit equals the resource rent from the fish stock.

The Open-Access Fishery

The equilibrium in an open-access fishery is known as the bionomic equilibrium (Gordon, 1954). The conditions for the bionomic equilibrium are: (i) harvest equal to natural growth; i.e., equation (2.1) is equal to zero, and (ii) profits (equation 2.5) equal to zero. From equation (2.5) we obtain expressions for the open-access stock and effort levels:

$$X_\infty = \left(\frac{c}{apK^{b-1}}\right)^{\frac{1}{g}} \tag{2.6}$$

$$K_\infty = \frac{pY}{c} \tag{2.7}$$

Hence, we can express the sustained yield Y_∞ in terms of price p and effort K:

$$Y_\infty = r\left(\frac{c}{paK_\infty^{(b-1)}}\right)^{\frac{1}{g}}\left[1 - \frac{1}{L}\cdot\left(\frac{c}{paK_\infty^{(b-1)}}\right)^{\frac{1}{g}}\right]. \tag{2.8}$$

Equilibrium supply is given by equations (2.7) and (2.8). While it is not possible to solve for explicit expressions for Y_∞ and K_∞ unless $b = g = 1$, it is possible to solve for Y_∞ and K_∞ numerically.

A pure schooling fishery is a special case of the Cobb-Douglas harvest function with a stock-output elasticity of zero. In this case, the cost of harvesting is independent of the stock level. Thus, depending on the price-cost relationship, the fishermen will either increase the fishing effort until the stock is depleted, or they will not harvest at all. Either way, the equilibrium supply would be zero. With $b = 1$ and $g = 0$, the stock would be depleted if $p > c/a$ (Bjørndal, 1988).

The Optimally Managed Fishery

We assume that a sole owner, whose objective is to maximise the present value of profits from the fishery, manages the fish stock. The present value of profits is as follows:

$$J = \int_0^\infty e^{-\rho t} \pi(t) dt, \tag{2.9}$$

where ρ is the social rate of discount. The problem is to maximise the present value of profits subject to equation (2.1). This is an optimal control problem, where X is the state variable and Y is the control variable. The maximum principle provides a set of necessary conditions for the optimum. If the profit function $\pi(X, Y)$ and the dynamic constraint $F(X) - Y$ are both concave in X and Y, then the necessary conditions are also sufficient. In our model this requires that the effort-output elasticity b is less than or equal to unity. This will not necessarily hold for the studied fishery. However, according to Arrow & Kurz (1970) the necessary conditions are also sufficient if the maximised Hamiltonian of the optimisation problem, $\tilde{H}^*(X(t), \lambda(t), t)$, is concave in $X(t)$.

The current value Hamiltonian corresponding to the optimisation problem of maximising the value of J in (2.9), subject to (2.1) is:

$$\tilde{H} = pY - c\left(\frac{Y}{aX^g}\right)^{\frac{1}{b}} + \lambda\left(F(X) - Y\right), \tag{2.10}$$

where $\lambda = \lambda(t)$ is the co-state variable representing the shadow value of an additional unit of fish at time t.

Before continuing, we will prove that the maximum principle provides sufficient conditions for a solution to the problem. Maximising the Hamiltonian (2.10) with respect to harvest rate Y and substituting for Y^* gives us the maximised Hamiltonian

$$\tilde{H}^* = X^{\frac{g}{1-b}}\left\{\left(\frac{c}{b}\right)^{\frac{b}{b-1}}\left[a\left(p-\lambda\right)\right]^{\frac{1}{1-b}} - \left[b\left(\frac{a}{c}\right)^{b}\left(p-\lambda\right)\right]^{\frac{1}{1-b}} X^{\frac{g}{b}}\right\}. \tag{2.11}$$

We only have to show that the maximised Hamiltonian is concave in X for $b > 1$, as we already know the conditions given by the maximum principle are sufficient for $b \leq 1$. Further, if the shadow price of the biomass λ is less than the price p, the optimal policy is $Y = 0$. Inserting $Y = 0$ into the Hamiltonian (2.10) gives us a concave function (as $F''(X) = -\frac{2r}{L} < 0$). It follows that if the maximised Hamiltonian (2.11) is concave in X for $b > 1$ and $p \geq \lambda$, the maximum principle provides sufficient conditions for the optimal management problem. By taking the second derivative of (2.11) with respect to X and doing some algebra, it can be showed that the maximised Hamiltonian is concave in X for relevant parameter values. The maximum principle will therefore be used to derive long-run supply curves for the optimally managed fishery in the following.

By applying the maximum principle, we can derive the following explicit expression for price:

$$p = \frac{c}{b}\left(\frac{Y}{aX^{g}}\right)^{\frac{1}{b}}\left[\frac{g}{X\left(\rho - r + 2rX/L\right)} + \frac{1}{Y}\right] \tag{2.12}$$

In addition to equation (2.12), the following condition must hold in equilibrium:

$$Y = F(X) = rX\left(1 - \frac{X}{L}\right) \tag{2.13}$$

Using equations (2.12) and (2.13), we can find optimal equilibrium combinations of price and yield. Clark (1990) refers to the resulting supply curve as the discounted supply curve.

We also want to find the equilibrium solution for a pure schooling fishery ($g = 0$). Using the first-order conditions from the optimal control problem, we find that the optimum is given by:

$$F'(X) = \rho \tag{2.14}$$

As there will be no harvesting if profits are negative, equilibrium supply in a pure schooling fishery is given by:

$$Y^{*} = \begin{cases} \frac{L}{4r}\left(r^{2} - \rho^{2}\right) & \text{if} \quad p \geq \frac{c}{Y^{*}}\left(\frac{Y^{*}}{a}\right)^{\frac{1}{b}} \\ 0 & \text{otherwise} \end{cases} \tag{2.15}$$

From equation (2.15) we can see that in a pure schooling fishery, the supply is independent of price and costs, as long as the price-cost ratio is above a certain level.

Comparing open access and optimal management, the possibility exists that the long-run supply from an open-access fishery is zero, which will be the case if the stock is driven to extinction. Equilibrium supply will be higher under optimal management than under open access.

We now turn to the estimation of supply curves.

2.3 Empirical Analysis

The estimating equation for the growth function in equation (2.2) is:[3]

$$(X_{t+1} - X_t) + Y_t = rX_t - \frac{r}{L}X_t^2 = \beta_1 X_t + \beta_2 X_t^2 + u_t, \tag{2.16}$$

where $\beta_1 = r$ in equation (2.2) and $\beta_2 = -r/L$. Consequently, the carrying capacity can be expressed as $-\beta_1/\beta_2$. The left-hand side of equation (2.16) represents the natural growth of the stock at time t, given by the sum of stock change and harvest during the period. The right-hand side is the logistic growth function. Equation (2.16) is estimated using ordinary least squares (OLS) based on data from the International Council for the Exploration of the Sea (ICES) for annual total biomass and landings for the

[3] Bjørndal (1988) developed and estimated a delay-difference model of population dynamics. Bjørndal & Conrad (1987) found that the Schaefer model was a good approximation of this more complicated model. As will be seen, the statistical fit of the model is also good.

period 1981-2001 with results presented in Table 2.1.[4] For details on the estimations, see Nøstbakken (2002). The more general growth function,

Table 2.1: **Estimated Growth Functions for North Sea Herring (t-statistics in parentheses)**

	OLS	IV-1 (OLS)	IV-2 (OLS)
$\beta_1 = r$	0.526 (4.40)	0.542 (4.50)	0.532 (4.31)
$\beta_2 = -r/L$	-9.99e-08 (-2.54)	-1.09e-07 (-2.75)	-1.04e-07 (-2.55)
L	5,266,955 (5.62)	4,991,479	5,135,011
Adjusted R^2	0.82	0.82	0.80
Durbin Watson	1.61	2.49	1.79

$X_{t+1} - X_t + Y_t = \beta_1 X_t + \beta_2 X_t^{\delta} + u_t$, is also estimated to allow us to test if it is appropriate to use the Gordon-Schaefer growth function. The data set is, however, too small to give us good estimates of three different parameters. Consequently, the t-values are very low (see Table 2.2), and the hypothesis $\delta = 2$ cannot be rejected at the 5% significance level. We therefore use the Gordon-Schaefer model estimated by OLS. According to the results pre-

Table 2.2: **Estimation Results from Nonlinear Least Squares Regression of a more General Growth Function.**

	Coefficient	t-value
r	0.355	0.83
L	364,831,200	0.04
δ	2.479	1.58
Adjusted R^2		
Durbin Watson		

[4]Source: Herring Assessment Working Group, ICES (2002a)

sented in Table 2.1, the intrinsic growth rate of the biomass r is about 0.53 and the carrying capacity of the environment L is about 5,270,000 tonnes. The estimate of the intrinsic growth rate is very close to the corresponding estimate reported by Bjørndal (1988) of 0.52, which was based on estimating a delay-difference model of population dynamics. Arnason et al. (2000) report an estimate of the intrinsic growth rate for Norwegian spring spawning herring of 0.47. Thus, the estimate of the intrinsic growth rate presented appears to be very robust.

Based on the estimated parameters, the stock level corresponding to maximum sustainable yield X_{msy} is 2,635,000 tonnes, with a corresponding maximum sustainable yield (MSY) of 698,275 tonnes.

Bjørndal & Conrad (1987) used Norwegian purse seine data for the period 1963 - 1977 to estimate a Cobb-Douglas production function. They obtained: $a = 0.06157$, $b = 1.3556$, and $g = 0.5621$. The parameter estimates show that the Schaefer production function is inappropriate for the North Sea herring fishery. The parameter g reveals, as expected, the output elasticity of stock size to be between zero and one. Thus, harvest will decrease with decreasing stock size, but is not very sensitive to changes. The parameter b indicates an output elasticity of effort larger than one. This means that increased effort is met with increasing harvest. This may be the result of economies of scale in the search for schools of herring.

Bjørndal & Conrad (1987) also estimated the production function for a pure schooling fishery as a special case. With $g = 0$ imposed, they obtained the following parameter estimates for the Cobb-Douglas production function by OLS regression: $a_s = 93.769$ and $b_s = 1.4099$. Even if the Cobb Douglas functional form, $Y = aK^bX^g$, resulted in the most plausible values for the bionomic equilibrium and open-access dynamics (Bjørndal & Conrad, 1987), the pure schooling fishery is an interesting case. As pointed out by Bjørndal (1988) the optimal stock levels under this assumption are always less than or equal to optimal stock levels with density-dependent costs.

Several countries harvest the North Sea herring stock. By estimating the production function using data from the Norwegian purse seine fleet, fishing effort K may be interpreted as an estimate of "purse seine equivalents" fishing herring in the entire North Sea (Bjørndal & Conrad, 1987). The parameters of the production function estimated by Bjørndal & Conrad (1987) will be used in the current analysis. Their estimation was for a time period when the fishery was unregulated, and econometric conditions for estimating a production function were satisfied. This would not be the case for later periods, due to varying regulations of the fishery. The implication of using these parameters is that the efficiency of the fleet, represented by the constant term a, may be somewhat underestimated due to technological development.

Cost data for the Norwegian purse seine fleet will be used. The Norwegian Directorate of Fisheries annually collects cost data on a sample of vessels. Cost data for purse seine vessels with cargo capacity 8,000 hectolitres and above is used in the analysis. Fixed costs are disregarded, because the vessels in question participate in several seasonal fisheries in addition to the North Sea herring fishery. This is appropriate, as the North Sea herring fishery is relatively minor compared to other fisheries and does not require any special equipment.

The price used is the average price paid to the boat owners for North Sea herring, adjusted by a factor of 0.65, which represents the boat owner's share of income. Adjusted prices and relevant costs for the period 1998 to 2000 are shown in Table 2.3. See Nøstbakken (2002) for a more thorough discussion. All prices and costs are in real 2001 NOK. Table 2.3 shows a

Table 2.3: **Price per Tonne, Variable Costs, and the North Sea Herring Fishery's Share of the Costs, 1998-2000.**

Year	1998	1999	2000
Price	1,547	1,210	1,318
Variable costs			
Fuel	1,063,687	1,520,629	2,358,402
Bait, ice, salt, and packaging	20,242	254,589	471,606
Miscellaneous	1,575,765	2,522,033	2,137,035
Total variable cost	2,659,694	4,297,251	4,967,042
Number of fishing days	260	250	273
Variable costs per fishing day	10,230	17,189	18,194
Fishing days, North Sea herring	60	60	60
Variable costs, North Sea herring	613,800	1,031,300	1,091,700

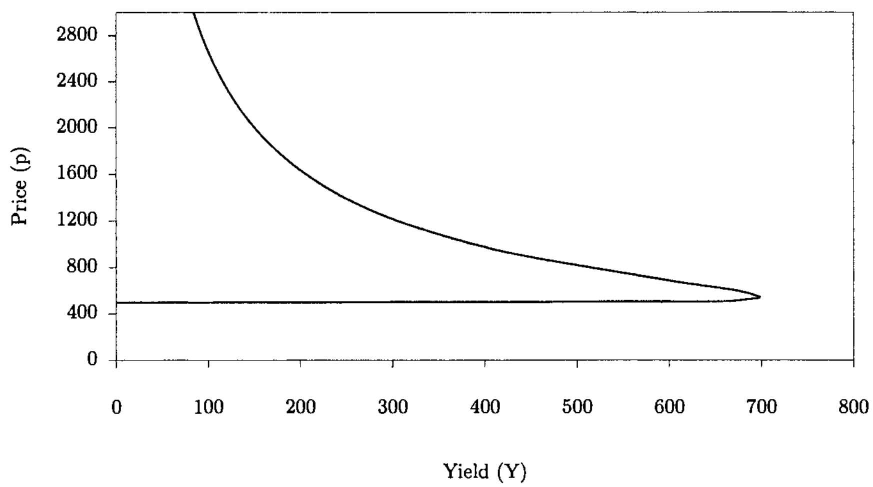
Source: Norwegian Directorate of Fisheries (Anon., 1998-2000)

substantial increase in costs from 1998 to 2000. The increase was particularly large from 1998 to 1999. One explanation is that a relatively large number of vessels were replaced that particular year. In addition, the price of fuel increased considerably during the period.

2.3.1 The Equilibrium Supply Curves

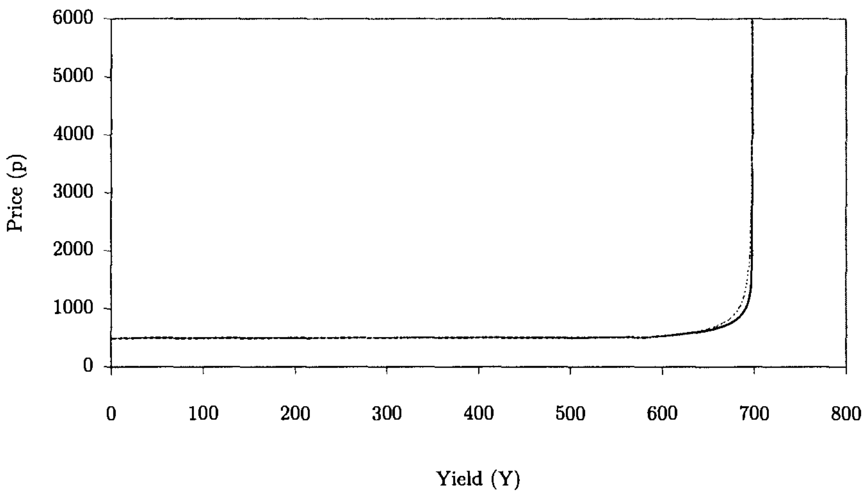
Using the estimated parameters, we are now able to numerically derive equilibrium supply curves. The open-access equilibrium supply curve for the cost $c = 1,091,700$, is shown in Figure 2.1. $c = 1,091,700$ represents the cost per purse seine vessel in the North Sea herring fishery in 2000 (see Table 2.3). The shape of the curve is backward bending as a consequence of the biological overfishing that occurs when effort exceeds the level corresponding to MSY (Clark, 1990).

Figure 2.1: **The Open-Access Equilibrium Supply Curve, c = 1,091,700 NOK (p in NOK/kg, yield in thousand tonnes).**



The supply is zero if the adjusted price is 495 NOK/tonne or less. The reason is that fishing is not viable at such low price levels. For prices above 495 NOK/tonne, the supply increases to the MSY, and subsequently decreases toward zero again. MSY = 698,275 tonnes is reached when the price is 544 NOK/tonne. Figure 2.2 shows the equilibrium supply curve

Figure 2.2: **The Discounted Supply Curve, c = 1,091,700 NOK, $\rho = 0.06$ (black line) and $\rho = 0$ (p in NOK/kg, yield in thousand tonnes).**



for the optimally managed fishery when $c = 1,091,700$ and alternative discount rates of 0% and 6%. For $\rho > 0$, the discounted supply curve is backward bending, but the degree of backward bending depends on the rate of discount employed. For small ρ, the degree of backward bending will be modest. For $\rho = 0$, the supply approaches MSY asymptotically as price increases.

Similar to the case of open access, the discounted supply will be zero if the price is 495 NOK/tonne or less. If the discount rate is 6%, supply will increase with price until $p_{msy} = 1,397$ NOK/tonne is reached and the supply is MSY = 698,275 tonnes. Subsequently, the supply decreases towards a level of 689,325 tonnes. Thus, even large changes in the price will not affect the discounted supply very much.

Figure 2.3: **Equilibrium Supply Curves for the Optimally Managed Pure Schooling Fishery, c = $1,091,700$ NOK and $\rho = 0$, $\rho = 0.06$, and $\rho = 0.18$ (p in NOK/kg, yield in thousand tonnes).**

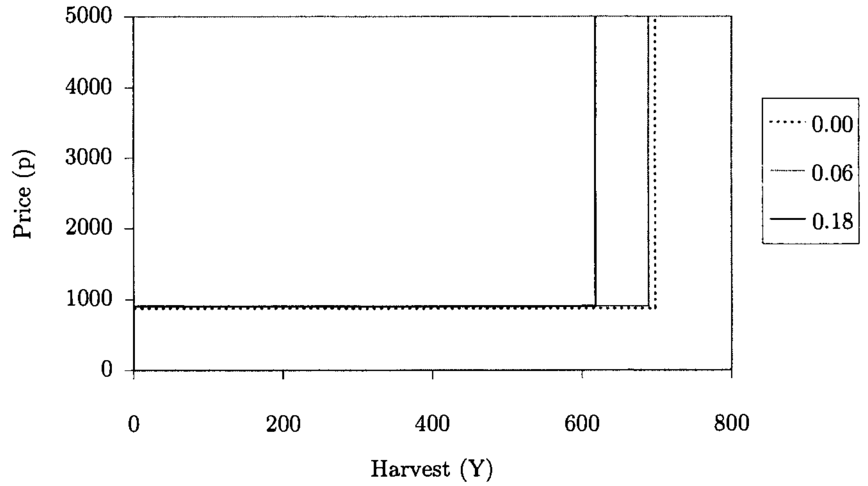


Figure 2.3 shows equilibrium supply curves for the optimally managed pure schooling fishery. In this fishery, the equilibrium supply will be zero if the price is less than 875 NOK/tonne. For prices above 875 NOK/tonne, the equilibrium supply is positive and independent of price as long as $\rho \leq r$. If $\rho > r$, the stoc

supply will be zero. The equilibrium supply is decreasing in the rate of discount. For prices above 875 NOK/tonne, the supply is MSY = 698,275 tonnes for $\rho = 0$ and 689,325 tonnes for $\rho = 0.06$. The optimally managed, pure schooling fishery represents limits for the optimal stock level.

2.3.2 Sensitivity Analysis

The open-access equilibrium supply curve is most sensitive to changes in the parameters of the production function; especially to changes in the parameters b and g. Changes in costs have a moderate effect on open-access supply. The supply curves for the optimally managed fishery are most sensitive to changes in the biological parameters. They are not very sensitive to changes in the discount rate. The effect of changes in costs on the discounted supply curve is little. For further details see Nøstbakken (2002).

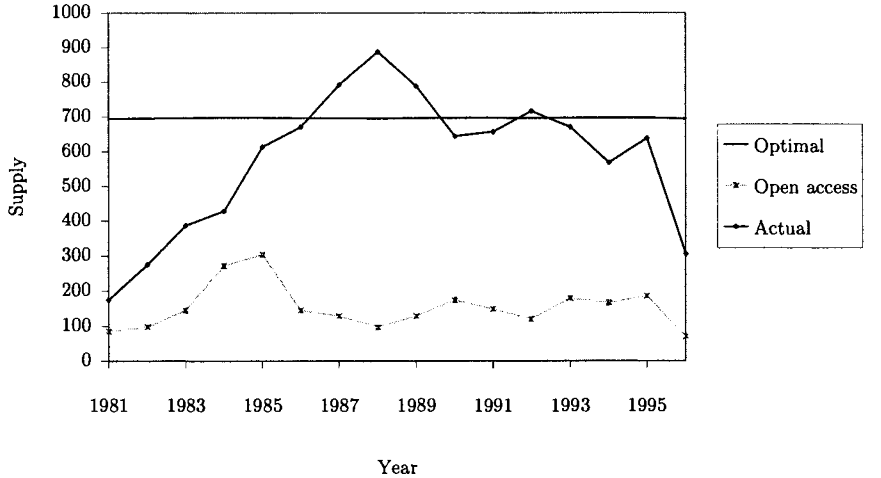
2.4 Effects of Regulations

We will now analyse the effect of actual regulations on the supply of North Sea herring and compare these to the open-access and optimally managed fisheries. These two cases represent extremes. Very few, if any, real-world fisheries are under such regimes, but these cases are of interest as benchmarks for other regulations. The following discussion will be divided into two periods, before and after 1996, because of an evident change in the regulatory regime that year.

2.4.1 Regulations 1981-1996

After a moratorium, the fishery was reopened in the southern North Sea in 1981 and in the central and northern North Sea in 1983. In 1983, the total biomass was about 2.7 million tonnes. From 1983 to 1988, there was a large increase in catches, resulting in a total catch of 888,000 tonnes in 1988 as can be seen in Figure 4. With MSY = 698,275 tonnes, the landings during the mid-1980s were clearly not sustainable.

Figure 2.4: **Equilibrium Supply under Open Access and Optimal Management,[a] together with Actual Supply,[b] 1981-1996 (Supply in thousand tonnes). Open Access and Optimal Management Harvests based on Prevailing Prices and Costs.**



[a]Discount rate $\rho = 0,06$
[b]Source: ICES (2002a)

Based on price and cost data from 1984, we can calculate the equilibrium supply and corresponding stock and fishing effort for the optimally managed and open-access fisheries. The results are shown in Table 2.4. The optimal stock level is about 2.66 million tonnes. This is approximately the same as the actual stock level in 1983. To maximise the resource rent from the stock, one should have harvested 698,200 tonnes per year. Instead, the stock was gradually reduced below the safe biological level because of extensive harvesting. Without any regulations in the fishery, the stock would have been reduced to a level of 575,100 tonnes, with annual catches of 271,500 tonnes (Table 2.4). Bjørndal & Conrad (1987) use a discrete time model to analyse the dynamics of an open-access fishery. They argue that with this model specification there is a greater likelihood of overshooting, severe depletion, and possible extinction. Thus, there may be depletion because of overshooting in the open-access case, instead of the stated equilibrium. Figure 2.4 shows the actual harvest each year from 1981 to 1996

Table 2.4: **Equilibrium under Open Access and Optimal Management, p = 1,151 NOK/tonne and c = $903,000$ NOK (Harvest and Stock in Tonnes, Fishing Effort in Number of Purse Seine Equivalents)**

	Harvest (Y)	Stock (X)	Fishing effort (K)
Open-access	271,500	575,100	326
Optimal management	698,200	2,658,900	347

and the harvest each year under optimal management and open access.[5]

[5]Harvests each year under optimal management and open access are based on the

While annual harvest varies considerably under open access, it is very stable under optimal management. The actual regulations in the North Sea herring fishery during this period were not optimal as they did not maximise rent. However, there were some regulations, distinguishing it from the open-access regime. Without these regulations, the stock would probably have been reduced at a faster pace than observed. In this sense, the regulations prevented the fishermen from catching even more herring, although the actual catches were far from sustainable. The regulatory regime might, therefore, best be termed "regulated open access" (Homans & Wilen, 1997).

2.4.2 Regulations 1996-2002

In May 1996, Norway and the European Union agreed on severe reductions in total quota to save the North Sea herring stock from collapse. Since 1998 the EU-Norway agreement has been in effect. To rebuild the stock to an acceptable level, the quotas were relatively small from 1996 to 2002. In 2002, the spawning stock exceeded 1.3 million tonnes, the limit defined by the EU-Norway agreement.

From 1996 onwards, the quotas agreed on by the EU and Norway have been set according to recommendations from ICES. For this reason, we also expect the quotas for 2003 to follow ICES recommendations. In this case, the TAC for the North Sea area will increase from 265,000 tonnes to 450,000

prevailing prices and costs.

tonnes in 2003.[6] Both prices and costs appear to have changed considerably

Table 2.5: **Equilibrium under Open Access and Optimal Management According to Prices and Costs in 1998, 1999, and 2000 (Prices in NOK/tonne, Costs in NOK, Harvest and Stock in Tonnes, Fishing Effort in Number of Purse Seine Equivalents).**

	1998	1999	2000
Price p	1,547	1,210	1,318
Cost c	613,800	1,031,300	1,091,700
Open access			
Harvest Y_∞	95,300	279,800	269,200
Stock X_∞	186,300	595,100	569,600
Fishing effort K_∞	240	328	325
Average catch per vessel	397.1	853.0	828.3
Optimal management[a]			
Harvest Y_∞	695,700	698,200	698,200
Stock X_∞	2,475,100	2,667,600	2,656,400
Fishing effort K_∞	356	346	347
Average catch per vessel	1,954.2	2,017.9	2,012.1
Actual state[b]			
Harvest	380,200	372,300	372,400
Stock	2,189,700	2,464,400	3,118,900

[a]Discount rate $\rho = 0.06$
[b]Source: ICES (2002a)

from 1998 to 2000. For this reason, the equilibrium supply will depend on what year the analysis is based. Table 2.5 shows equilibrium supply and corresponding stock and fishing effort for the years 1998, 1999, and 2000. The table also shows the actual harvest and stock level each year.

While the equilibrium supply was quite stable from 1998 to 2000 in the

[6]ICES Subarea IV and Division VIId. Autumn spawning North Sea herring is also caught in Skagerrak and Kattegat (Division IIIa).

optimally managed fishery, the opposite is true for the open-access fishery. Under an open-access regime, the equilibrium supply was 95,000 tonnes in 1998 and 280,000 tonnes in 1999. As can be seen in Table 2.5, the corresponding stock levels are 186,000 tonnes and 595,000 tonnes. According to ICES, the minimum biological acceptable level for the North Sea herring spawning biomass is 800,000 tonnes. With a total biomass of less than 600,000 tonnes, the stock would have been in danger of extinction under an open-access regime.

If the fishery was optimally managed, the stock would be about 2.6 million tonnes in all three years (Table 2.5). The actual stock level in 2000 was about 3.1 million tonnes. Despite this, the quotas were relatively small in 2001 and 2002 to let the stock grow even more. According to data for 2000, a stock of 2.66 million tonnes, with a corresponding annual harvest of 698,200 tonnes, would maximise the rent from the stock (Table 2.5). Thus, annual harvest would be almost as large as the MSY.

For 2000, the optimally managed fishery included a fishing effort of 347 purse seine equivalents in the North Sea herring fishery. This would allow each purse seine equivalent to harvest about 2,010 tonnes annually, on average. In 2001, total North Sea herring landings were 364,000 tonnes. By assuming that each purse seine equivalent catches as much North Sea herring as the average Norwegian purse seiner, we find that 498 purse seine equivalents participated in the North Sea herring fishery in 2001. Thus, actual fishing effort in 2001 was considerably greater than under an optimally managed regime. In addition, the total catch was smaller, resulting in a much smaller average catch per purse seine equivalent in the actual fishery than in the optimally managed fishery.

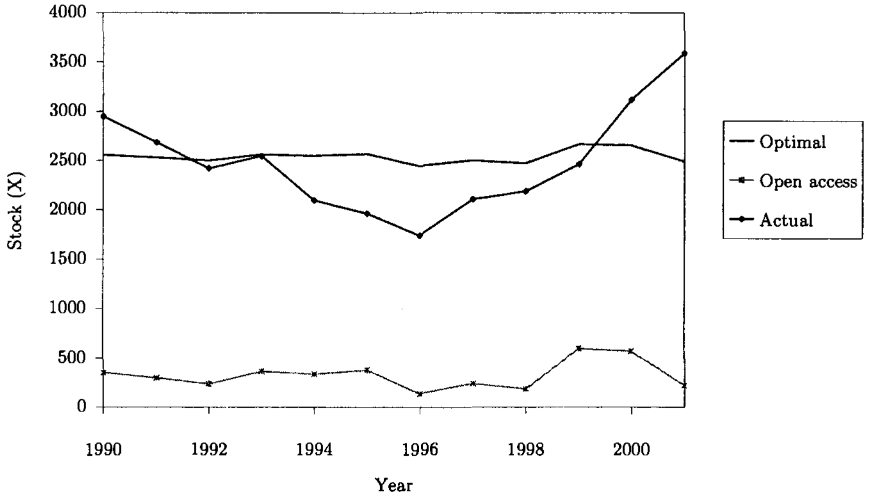
The fact that the EU and Norway did not increase TAC in 2001 or 2002, indicates that they wanted to stabilise the stock at a higher level than what maximises economic rent. ICES (2002b) gives different catch options for 2003, which reflect both the ICES recommendations and the EU-Norway agreement. All scenarios result in a spawning stock of 2.2 million tonnes and a total catch between 620,000 and 635,000 tonnes. If the EU and Norway continue to follow ICES recommendations, stabilisation with an annual harvest of about 630,000 tonnes is expected. Using the logistic growth function from equation (2.2), we estimate the corresponding total biomass level to be 3.5 million tonnes.

The regulatory regime that has been in force since 1996 appears to result in a lower supply of North Sea herring than what would have been the case if the fishery was under optimal management. Because of the shape of the logistic growth function, moderate stock reductions would have increased the sustainable yield.

2.4.3 The Effect of the 1996 Change in Regulations

The change in regulations in 1996 seems to have had considerable effects on both stock level and supply. Before 1996, annual landings were unsustainable. This caused the stock to decrease every year, and from 1992 onwards the stock was smaller than the stock level under optimal management. After the change in 1996, the stock increased from year to year, and from 2000 onwards the stock has been larger than the optimal level. This development is illustrated in Figure 2.5.

Figure 2.5: **Equilibrium Stock (in thousand tonnes) under Open Access[a] and Optimal Management,[a,b] and Actual Stock,[c] 1990-2001**



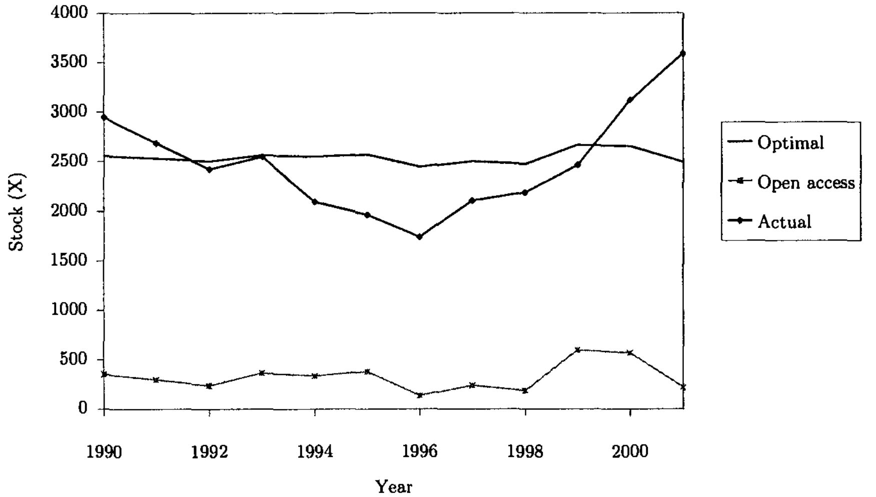
[a]The 2001 equilibrium stock is based on costs in 2000.
[b]Discount rate $\rho = 0,06$
[c]Source: ICES (2002a)

The change in regulations in 1996 is also evident in Figure 2.6. This figure shows equilibrium supply under open access and optimal management, together with actual supply and calculated sustainable yield based on actual stock level.[7] The optimally managed fishery results in the highest supply, while the open-access fishery results in the lowest. The difference

[7]Sustainable yield Y_A based on actual stock level X_A is calculated as follows: $Y_A = rX_A(1 - X_A/L)$

between actual catches and estimated catches based on actual stock levels is relatively large. This is a consequence of the fishery not being in equilibrium. As expected, the difference is particularly large after 1996.

Figure 2.6: **Equilibrium Supply under Open Access[a] and Optimal Management,[a,b] together with Actual Supply and Calculated Equilibrium Supply Based on Actual Stock Level, 1990-2000 (in thousand tonnes).**



[a]The 2001 equilibrium stock is based on costs in 2000.
[b]Discount rate $\rho = 0,06$

2.5 Summary

Different regulations can have a substantial impact on the supply of North Sea herring. It has been argued that the annual equilibrium supply can vary from zero, in the case where the stock is driven to extinction under open access, to a sustainable annual yield of 690-700 thousand tonnes. The reason for this difference is the effective means of harvesting schooling fish stocks, which makes the harvesting of herring economically viable even at very low stock levels.

In this paper we have derived and estimated equilibrium supply curves for the open-access and optimal management fisheries. A sensitivity analysis was subsequently carried out. This analysis showed that the open-access supply curve was most sensitive to changes in the parameters of the production function, while the discounted supply curve was most sensitive to changes in the biological parameters. Moderate changes in the discount rate were found to have little effect on equilibrium supply.

Different regulations, both actual and theoretical, were evaluated with respect to effects on supply, stock level, and fishing effort. A change in the actual regulations was evident in 1996. From 1996 onwards, the quotas have been relatively small. This has allowed the stock to approach a higher level than what maximises rent. Because of this, the annual supply is smaller than in an optimally managed fishery. However, the supply would have been much smaller under an open-access regime.

This paper represents one of the few empirical analyses of supply functions in the literature. The results have been used to gain a better understanding of the consequences of various regulations of the North Sea herring fishery. The present analysis could be extended in a number of ways. One possibility would be to introduce uncertainty in the model of population dynamics. Another possibility would be to combine the supply curves with estimations of demand curves in order to study the market for North Sea herring.

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Chapter 3

Stochastic Modelling of the North Sea Herring Fishery under Alternative Management Regimes

Abstract

Until 1977 the North Sea herring fishery was an open-access fishery. To save the herring stock from total depletion the fishery was closed from 1977 until 1981. Various regulations have been in effect ever since. In this study, a discrete-time stochastic bioeconomic model is developed to analyse the North Sea herring fishery under alternative management regimes. It is shown how catches and harvest policies change with the price of herring. Feedback policies are found for the optimally managed fishery. The management of the North Sea herring after the moratorium was lifted in 1981 is evaluated. The results indicate that the management has been suboptimal. Under optimal management the fishery should have stayed closed until 1983. We also find that the current stock is significantly larger than what maximises net revenues from the fishery.

3.1 Introduction

In most bioeconomic models, price is assumed fixed. This is a simplifying assumption that is often made when analysing the optimal exploitation of a renewable resource. The aim of this paper is to investigate and quantify how the harvest quantity of fish varies with price under different regulations. Such knowledge is important with respect to analysis of the fishery under optimal management, open access, and other regulatory regimes. Nøstbakken & Bjørndal (2003) derived and estimated supply curves for the North Sea herring fishery. Apart from this, there are few empirical applications of supply functions in the literature. In Nøstbakken and Bjørndal's analysis, a deterministic bioeconomic model was used. While the deterministic case offers some useful benchmarks, there are many sources of uncertainty that influence real-world fisheries. In this paper, a stochastic bioeconomic model will be used to analyse the North Sea herring fishery under different management regimes. The current analysis will, to some degree, be an extension of the work in Nøstbakken & Bjørndal (2003).

Two different production functions will be used to explain harvesting of North Sea herring. While the analysis will show that the difference between the two under optimal management is modest, the choice of the harvest relationship has big implications for the predictions made under open access. We find that the choice of production function is crucial for the outcome of open access in the fishery, although the two production functions give similar predictions for higher stock levels.

The optimal management of North Sea herring was analysed by Bjørndal (1987, 1988). His analyses are based on deterministic models of the fishery. By introducing uncertainty into the bioeconomic model, we might get further insight into the optimal management of a pelagic fishery such as the North Sea herring fishery. In the stochastic setting, we will find feedback policies for the optimally managed fishery. Optimal feedback policies depend on stock level, but also on the price of herring. In an attempt to evaluate how efficient the management of the North Sea herring has been in the past, the optimal feedback policies are applied to the fishery for the period 1981-2001.

The rest of the paper is organised as follows. In the next section, a description of the North Sea herring fishery is given, and the bioeconomic model is presented and estimated. In section 3.3, numerical analyses are undertaken. The final section summarises and concludes.

3.2 Bioeconomic Model and Empirical Analysis

The first part of this section gives a short overview of the North Sea herring fishery. The second part presents the bioeconomic model, while parameter values for the model are estimated in the third part.

3.2.1 The North Sea Herring Fishery[1]

The North Sea autumn spawning herring (*Clupea harengus*) is a pelagic stock that lives on plankton. The stock was severely depleted in the 1960s and 1970s due to overfishing under an open-access regime combined with the development of very effective fish-finding technology (Bjørndal, 1988). In 1977, the fishery was closed to allow the stock to recover. Since the moratorium was lifted, regulations have been in effect. Nevertheless, in the mid-1990s the stock once again was below safe biological limits, and in 1996 the total quota was reduced to save the stock from collapse. To rebuild the stock, the quotas have been relatively small from 1996 onwards. Recent stock estimates show that it has been rebuilt above the level that guarantees good recruitment (ICES, 2003). While the total quota was held constant from 1999 to 2002, the quota increased with about 40 percent from 2002 to 2003.

After the introduction of extended fisheries jurisdiction, the North Sea herring has been considered a common resource between Norway and the European Union (EU). In December 1997, the parties agreed on a management scheme for the stock, the EU-Norway agreement, specifying stock objectives and how to set catch quotas. This agreement has been in force since 1 January 1998. According to the EU-Norway agreement, the total quota for the directed fishery shall be allocated among the two parties with 29% to Norway and 71% to the EU. In addition, the EU gets the entire

[1]This section is based on Nøstbakken & Bjørndal (2003).

bycatch quota.

3.2.2 The Model

Reed's (1979) stochastic stock-recruitment model is used. This is an aggregated model, and uncertainty is incorporated in a way that makes the model tractable. The Reed (1979) model can be written as follows:

$$X_{t+1} = z_{t+1}G(S_t) \tag{3.1}$$

$$S_t = X_t - Y_t, \tag{3.2}$$

where X_t is the total biomass at the beginning of period t, S_t is escapement, and Y_t is harvest. z_{t+1} are independent and identically distributed (iid) random variables with mean one and constant variance, observed at the beginning of period $t+1$. $G(S_t)$ is a growth function.

z_{t+1} can be thought of as environmental shocks that occur between last period's harvest and the current period's recruitment. This means that after observing the random variable in one period, one knows the current period's recruitment level with certainty. The fishery manager can thus set the quota at the beginning of every period, after the uncertainty has been revealed. In most real-world fisheries, fisheries managers do not know the exact stock level when setting quotas. Clark & Kirkwood (1986) deal with this by modelling a fishery in a similar manner to Reed's, but where the uncertainty is revealed after the harvest level has been determined. Within this framework, they show that the optimal harvesting policy is different from the optimal policy in the Reed model. Weitzman (2002) also uses a model similar to Reed's, but where regulatory decisions are made before the period's recruitment is known. He uses his model to compare different management instruments.

The Reed model seems to give a reasonable representation of the growth in the North Sea herring stock, as we shall see in the next section where the empirical analysis is described. However, as we noted above, the Reed model assumes uncertainty is revealed before harvesting policies are set. This is a drawback with this model specification, because the managers do not know the exact level of the North Sea herring stock when setting quotas. The advantage of using Reed's model is that it is much more tractable than, for example, a specification similar to Clark & Kirkwood (1986).

Further, it is assumed that harvest in period t is given by an industry production function:

$$Y_t = H(K_t, X_t) \tag{3.3}$$

This function relates harvest, Y_t, to effort, K_t, and stock size, X_t. According to Bjørndal & Conrad (1987b), search for schools is of predominant importance in a fishery on a schooling species like herring. Thus, in such fisheries the number of participating vessels may be an appropriate measure of effort, an assumption that will be made throughout this paper.

By assuming a constant cost per unit effort, the net revenue for the industry can be written as:

$$\pi_t = pY_t - cK_t, \tag{3.4}$$

where p is the price per unit of harvest and c is the unit cost per vessel per season.

Production Functions and Optimal Harvest

Two specifications of the aggregate production function in equation (3.3) will be considered, the Spence (1974) and the Cobb-Douglas production functions. In this section, these relationships and their optimal feedback policies are presented.

In Reed (1979), the Spence harvest function is used:

$$Y_t = X_t(1 - e^{-qK_t}), \tag{3.5}$$

where $q > 0$ is a catchability coefficient. We see that $Y_t \to X_t$ as $K_t \to \infty$ and it is thus very difficult to harvest the stock to total extinction within this model.

The variable cost per unit of fish caught at each point in time can be written as:[2]

$$C = C(X_t, Y_t) = \frac{c}{q}\left[\ln(X_t) - \ln(X_t - Y_t)\right] = \frac{c}{q}\left[\ln(X_t) - \ln(S_t)\right]. \quad (3.6)$$

Net revenues are thus:

$$\pi_t = pY_t - (c/q)[ln(X_t) - ln(S_t)]. \quad (3.7)$$

As Reed (1979) noted, this can be written as an additive separable function of the state variable X and the control variable S. We then have $\pi_t = N(X_t) - N(S_t)$, where $N(m) = pm - (c/q)ln(m)$.

In an optimally regulated fishery, we assume that a sole owner or a social planner, whose objective is to maximise the expected value of discounted net revenues from the fishery, manages the fish stock. He faces the following maximisation problem:

$$\max_{\{S_t\}} E_0\left[\sum_{t=0}^{T} \rho^t \{N(X_t) - N(S_t)\}\right], \quad (3.8)$$

subject to (3.1), (3.2), and X_0 given. $\rho = 1/(1+\delta)$ is the discount factor, and δ is the discount rate. The maximisation problem can be solved using stochastic dynamic programming. It can be shown that the optimal harvest policy is a constant-escapement policy (Reed, 1979), where the optimal

[2] $Y_t = X_t(1 - e^{-qK_t}) \Rightarrow e^{-qK_t} = 1 - \frac{Y_t}{X_t} = \frac{X_t - Y_t}{X_t} \Rightarrow K_t = \frac{1}{q}[ln(X_t) - ln(X_t - Y_t)]$

escapement level must maximise the following equation:[3]

$$W(S) = \rho E_z [N(zG(S))] - N(S) \tag{3.9}$$

This equation can be solved numerically for the optimal escapement level S^*. The optimal policy can be expressed as:

$$Y_t = \begin{cases} (X_t - S^*) & if \quad X_t > S^* \\ 0 & if \quad X_t \leq S^* \end{cases} \tag{3.10}$$

Let us now turn to the Cobb-Douglas production function, which can be expressed as

$$Y_t = aK_t^b X_t^g. \tag{3.11}$$

The parameter a in the relationship represents the efficiency of the fishing fleet. b and g are output elasticities of stock size and effort, respectively. Because of the herring's schooling behaviour, harvesting can be viable at very low stock levels and the parameter estimate of g is therefore expected to be less than one (Bjørndal, 1987).

As opposed to the Spence function, effort does not have to approach infinity as $Y_t \rightarrow X_t$ when we use the Cobb-Douglas production function. It is consequently possible to drive the stock to zero without having an infinite number of vessels participating in the fishery.

Cost per unit of harvest and net revenues are given by equations (3.12)

[3]See Conrad (2004) for the derivation of this expression.

and (3.13):

$$C = c\left(\frac{Y_t}{aX_t^g}\right)^{\frac{1}{b}} \tag{3.12}$$

$$\pi_t = pY_t - c\left(\frac{Y_t}{aX_t^g}\right)^{\frac{1}{b}} \tag{3.13}$$

In an optimally regulated fishery, the manager would want to maximise the expected value of discounted net revenues from the fishery. Unfortunately, it is not possible to express net revenues given by equation (3.13) as a separable function of the state and the control variables. This means that we do not have a simple way of finding the optimal feedback policy for the fishery.

As we cannot solve the maximisation problem analytically, we will instead search for an optimal feedback policy among possible policies. The feedback policy can be specified in an infinite number of ways and we do not know the form of the optimal policy. The current analysis will therefore be restricted to finding the optimal *linear* feedback policy, given by the equation

$$Y_t = \alpha + \beta X_t. \tag{3.14}$$

In Pindyck's (1984) continuous-time models, linear feedback policies emerge in three examples. Our search for optimal linear feedback policies thus seems fairly reasonable, although there might exist non-linear policies that would outperform the linear policies.

Harvest in any year can for obvious reasons never exceed the total biomass. In most fisheries it is also impossible to have a negative harvest. We therefore add the restriction $0 \leq Y_t \leq X_t$, that must hold for all t. The upper boundary condition for Y_t is not expected to be binding, since total extinction of a fish stock with an intrinsic growth rate as high as the herring's is very seldom optimal. With these restrictions on Y_t, we are searching for a feedback policy which is not strictly linear.

Vessel Dynamics

In accordance with Gordon (1954), it will be assumed that vessel entry and exit under open access follows the sign and size of net revenues per vessel. Fleet dynamics are assumed to occur according to the following equation:

$$K_{t+1} - K_t = n\frac{\pi_t}{K_t}, \tag{3.15}$$

where $n > 0$ is an adjustment parameter. If net revenues per vessel are positive, effort will increase. If net revenues per vessel are negative, effort will decrease.[4]

In the optimally regulated fishery, we assume that the optimal number of vessels participate in the fishery every period. Consequently, there will be no transition period if the optimal number of vessels changes from one season to the next. This is a simplifying assumption implying that

[4]This is perhaps a naive assumption considering the large literature on fisherman behaviour, including entry and exit decisions in fisheries (see e.g. Bockstael & Opaluch, 1983; Ward & Sutinen, 1994).

vessels becoming redundant in the North Sea herring fishery immediately is needed and employed in other fisheries. The question of optimal fleet size is more complicated and calls for a joint analysis of all fisheries in which the fishing fleet participates. Nevertheless, being relatively minor compared to other fisheries, the North Sea herring fishery's influence on optimal fleet size is modest.

3.2.3 Empirical Analysis

The empirical content of the model consists of the specification and estimation of the stock-recruitment function, and of the production and cost functions.

Stock-Recruitment Function

A specification of stock-recruitment corresponding to the deterministic part of equation (3.1) is given by the following logistic function:

$$X_{t+1} = G(S_t) = S_t\left(1 + r - \frac{rS_t}{L}\right), \tag{3.16}$$

where r and L represent the intrinsic growth rate and carrying capacity of the stock, respectively (Clark, 1990). This equation was estimated by ordinary least squares using annual data on total biomass and harvest for the North Sea herring for the period 1960-2002 obtained from the International

Council for the Exploration of the Sea (ICES).[5] Parameter estimates are presented in Table 3.1. The Durbin-Watson statistic given in the Table 3.1

Table 3.1: **Estimates of the Parameters of the Stock-Recruitment Function.**

Parameter	Estimated coefficient	Standard Error
	OLS	
r	0.432	0.075
L	6,677,528	1,549,772
Adjusted R^2	0.988	
Durbin Watson	1.319	
	OLS-Auto	
r	0.462	0.093
L	5,713,479	1,168,269
Adjusted R^2	0.979	
Durbin Watson	2.060	
ρ	0.298	

indicates that first-order autocorrelation might be a problem, since the test rejects the null hypothesis of no first-order autocorrelation. The Breusch-Godfrey Lagrange multiplier test of autocorrelation of order P was used to test the logistic equation for autocorrelation of order $P \in [1, 5]$. The null hypothesis of no autocorrelation was rejected for $P = 1$ (5% significance level). For $P > 1$, the null hypothesis could not be rejected.

Table 3.1 also presents the regression results from estimating the logistic function using the Cochrane-Orcutt transformation to correct for first-order autocorrelation. After the correction, the point estimate of the carrying ca-

[5]The Gompertz and Ricker functional forms were also estimated. However, the logistic function resulted in the best fit and was therefore preferred.

pacity is smaller while the estimated growth rate is nearly unchanged. The Durbin Watson test statistic implies that there is no first-order autocorrelation after the transformation. In the remainder of the paper, we use parameter estimates corrected for autocorrelation.

According to the regression results, the intrinsic growth rate of the biomass is $r = 0.46$ and the carrying capacity of the environment is $L = 5,713,480$ tonnes. The escapement level that maximises annual sustainable harvest is thus $S_{MSY} = \frac{L}{2} = 2,856,740$ tonnes. The corresponding maximum sustainable yield and biomass are $MSY = \frac{rL}{2} = 660,335$ tonnes and $X_{MSY} = \frac{(2+r)L}{4} = 3,517,075$ tonnes.

Estimated growth functions for herring can be found in several papers. Bjørndal (1988) and Nøstbakken & Bjørndal (2003) estimate growth functions for North Sea herring using data for the years 1947-1981 and 1981-2001, respectively. Arnason et al. (2000) estimate a growth function for Norwegian spring-spawning herring using data for the years 1950-1995. However, in these papers it is assumed that growth is determined by biomass X_t and not by escapement S_t as in the model estimated here. The three papers mentioned above report intrinsic growth rates of 0.52, 0.47, and 0.53, respectively. Our estimate of intrinsic growth rate, as reported in Table 3.1, thus seems to be robust. In addition, all the estimated parameters presented in Table 3.1 are significant at the 5% significance level and the estimated equation explains over 98% of the variation in the data. Modelling the growth as a function of escapement as opposed to biomass at the beginning of the period seems to result in a higher adjusted R^2 when estimating recruitment to the herring fishery. Bjørndal's (1988) estimate of carrying capacity for the North Sea herring is a spawning stock of 3.55 million tonnes, while Nøstbakken & Bjørndal (2003) reports a total stock of 5.27 million tonnes. In comparison, our estimate seems reasonable.

The model assumes the mean of z_{t+1} is one. Unless otherwise stated, we make the additional assumptions that the variance of z_{t+1} is $\sigma_z^2 = 0.05$ and that z_{t+1} is log-normally distributed.[6] Ideally, we would estimate the statistical properties of z_{t+1} based on the residuals from the regression of equation (3.16). With autocorrelated residuals, however, estimated z values will not be independent and identically distributed (iid) as assumed in the Reed (1979) model.[7] If the stochastic variable is not iid, it is not possible to derive an analytic solution to the optimisation problem. We therefore treat the z values as iid. The fact that the z values are correlated means, nonetheless, that knowing the value of z in one period enables one to make better predictions about future z values. The assumption that the stochastic variable is iid thus makes it more difficult for a social planner to optimise expected net revenues from the fishery than it would be in the case when the z values are correlated. The net benefits from the fishery could therefore be higher under optimal management than what we find

[6]The lognormal distribution ensures that all z values are non-negative

[7] Spulber (1982) extends the Reed (1979) model by assuming the random variable follows a general Markov process, i.e., $z = \phi(\cdot|z)$, where $\phi(\cdot|z)$ is a given probability function.

in the subsequent analysis by assuming iid z_{t+1}.

Vessel Dynamics, Production Functions, Costs, and Prices

Bjørndal & Conrad (1987a) analyse capital dynamics in the North Sea herring fishery. They estimate several fleet-adjustment equations but unfortunately not equation (3.15). Data presented in Bjørndal and Conrad (1987b; 1987a) are therefore used to estimate the adjustment parameter n in equation (3.15). This gives us a point estimate of $n = 10^{-1}$.[8] Unless otherwise stated, this estimate is used in the analysis.

Bjørndal & Conrad (1987b) estimate four production functions based on data for Norwegian purse seine vessels in the North Sea herring fishery, 1963-1977. The two functions that best fit the data, along with Bjørndal and Conrad's parameter estimates, are used in the current analysis.[9] These are the Spence production function (equation 3.5) with $q = 0.0011$, and the Cobb-Douglas production function (equation 3.11) with $a = 0.06157$, $b = 1.356$, and $g = 0.562$.

Following Nøstbakken & Bjørndal (2003), cost data for Norwegian purse seine vessels with cargo capacity 8,000 hectolitres and above is used in the analysis. Fixed costs are disregarded, since the vessels in ques-

[8] OLS estimation: t-value=2.08, adjusted R^2=0.192, and $DW_{(1,14)} = 1.435$.

[9] Bjørndal and Conrad's estimation was for a time period when the fishery was unregulated and econometric conditions for estimating a production function were satisfied. This would not be the case for later periods due to varying regulations of the fishery. The implication of using these parameters is that the efficiency of the fleet may be somewhat underestimated due to technological development.

tion participate in several seasonal fisheries in addition to the North Sea herring fishery. This is appropriate, as the North Sea herring fishery is relatively minor compared to other fisheries and does not require any special equipment. The variable cost does not include costs to crew the vessels, since crew remuneration represents a constant share of the vessel's revenues. The income is, therefore, adjusted by a factor that represents the boat owner's share. The price used in the analysis is average price paid to the boat owners for North Sea herring, adjusted by a factor of 0.65, which represents the boat owner's share of income. All prices and costs are in nominal NOK. For 2001, the adjusted average price is 2,465 NOK/tonne, and variable cost per vessel is 1,189,565 NOK/year. See Nøstbakken & Bjørndal (2003) for details on cost and price estimation. A 6% discount rate is used in the analysis.

3.3 Numerical Analysis

In this part, the North Sea herring fishery is analysed by using the two production functions. In both cases, the open-access fishery and the optimally regulated fishery are considered. Stochastic simulations are used in the analysis. All simulations are programmed and run in Matlab.

3.3.1 Model 1: The Spence Production Function

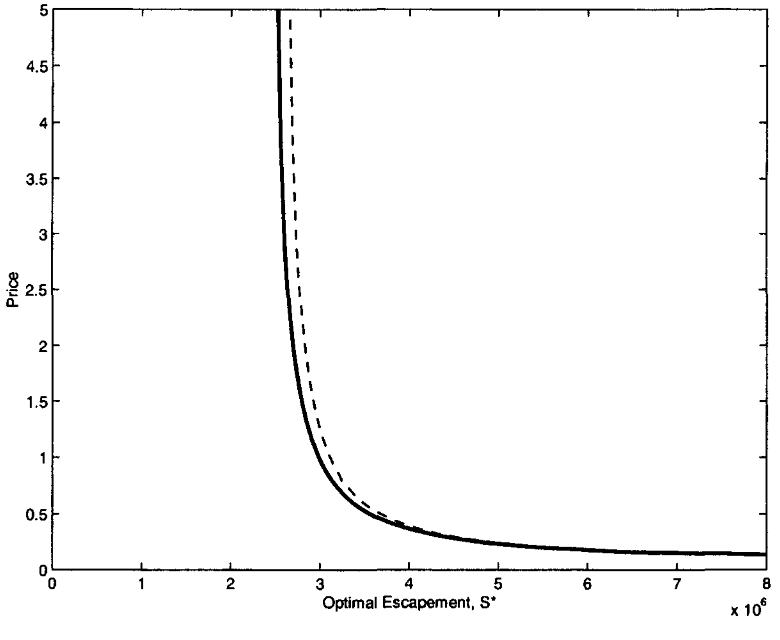
In the following section, the Spence harvesting relationship is used to analyse the optimally regulated and the open-access fisheries.

The Optimally Regulated Fishery

By stochastic simulations, the optimal escapement level can be found for given price, cost, and discount factor. Figure 3.1 shows the relationship between optimal escapement level and price. The optimal escapement level is not very sensitive to changes in the variance of z_{t+1}. For low prices, the figure shows that there is no difference between the curves that represent optimal escapement levels for $\sigma_z^2 = 0.05$ and $\sigma_z^2 = 0.20$. As price increases, the difference between the curves grows, but not very much. For price $p = 5$ NOK/kg, the difference in optimal escapement level is about 136,000 tonnes. As $p \to \infty$, the optimal escapement level approaches 2.524 million tonnes ($\sigma_z^2 = 0.05$). The optimal escapement level is thus very insensitive to price changes for prices above $p = 3$ NOK/kg. For prices below $p = 0.2$ NOK/kg, the escapement level is higher than the carrying capacity of the environment L. Consequently, for prices below $p = 0.2$ NOK/kg, there is no harvesting.

By simulating the fishery under the optimal harvest policy over a long time period, we can approximate the long-run statistical distributions of X, Y, etc. Figure 3.2 shows the average long-term levels of biomass and

Figure 3.1: **Model 1: Optimal Escapement Level. Variance $\sigma_z^2 = 0.05$ (–) and $\sigma_z^2 = 0.20$ (c=1,189,565 NOK, $\delta = 0.06$).**



harvest for different prices with confidence intervals.[10] For harvest, only the upper confidence limit can be seen - the lower level is below zero. The confidence levels seem to be fairly constant for different prices. We also find that the relative variation in annual harvest is much higher than the variation in biomass. For prices above $p = 2$ NOK/kg, biomass is some 3 million tonnes and the corresponding harvest is close to 700,000 tonnes. The shape of the harvest curve in Figure 2b is very similar to Nøstbakken and Bjørndal's (2003) discounted equilibrium supply curve for the North Sea herring fishery. However, the current stochastic analysis implies positive harvest levels for prices significantly lower than the price where harvest occurs in Nøstbakken and Bjørndal's deterministic analysis.

The Open-Access Fishery

Stochastic simulations of the open-access fishery are run for different prices ($N = 1,000$ simulations over $T = 200$ years). The carrying capacity of the environment L was used as the initial value for biomass, and the initial number of vessels was set to $K = 120$. As price approaches infinity, so does effort, and escapement $S \to \infty$. However, the simulation results show that the stock can be severely depleted even at more realistic prices than $p \to \infty$.

[10]A 66-percent confidence interval is shown in the figure, i.e., the mean plus or minus one standard deviation. 66-percent confidence intervals are used in the remainder of the paper.

Figure 3.2: **Model 1: Optimal Stock and Harvest with Confidence Intervals for Different Prices at Time t = 100.**

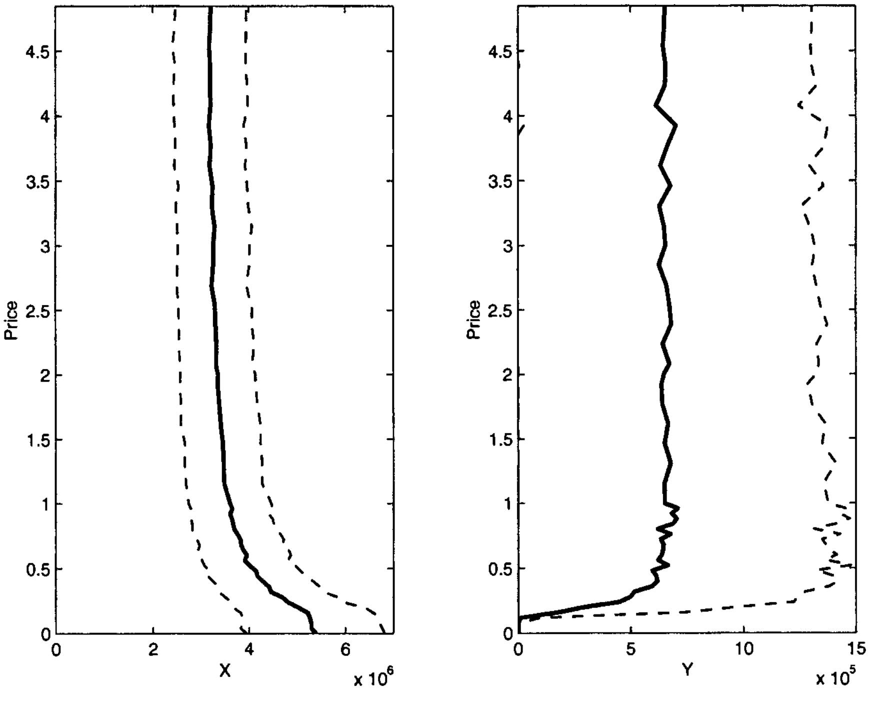


Figure 3.3: **Model 1: Open-Access Stock and Catch Dynamics with Confidence Intervals (c = 1,189,565 NOK, p = 2 NOK/kg).**

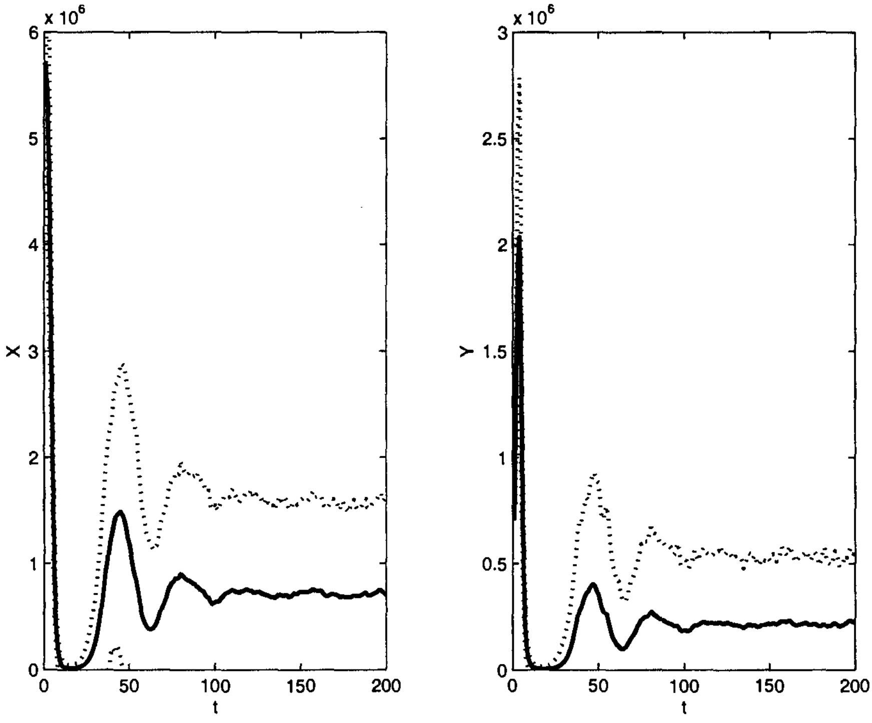


Figure 3.3 gives stock and catch dynamics with confidence intervals for price $p = 2$ NOK/kg. The long-term equilibrium stock level for this price is about 710,000 tonnes with a corresponding annual catch of about 215,000 tonnes. There is overshooting and subsequently damped oscillation toward the equilibrium levels of biomass and harvest. The number of vessels in the fishery also oscillates toward the long-term equilibrium level, as can be seen in Figure 3.4a. If a different adjustment parameter had been used, the degree of overshoot would have been different. Both expected biomass and catch fall almost to zero where they settle for several periods. In some of these periods, the biomass is under 20,000 tonnes, and the annual harvest is as low as about 5,000 tonnes. As mentioned earlier, the stock cannot be driven to zero unless $K \to \infty$. This is why the stock after a fairly long time period starts growing again and subsequently stabilises at the open-access equilibrium level.

If a different adjustment parameter had been used, the degree of overshoot would have been different (see Figure 3.4b, where $n = 5 \cdot 10^{-1}$). The dramatic initial increase in K can also be explained by the initial values of biomass and number of vessels. The small number of vessels that harvests from the relatively large stock of size L in the first period earns very high net revenues. Since it was assumed that vessel dynamics follow the sign and size of net revenues per vessel, the subsequent increase in the number of vessels is very high.

Figure 3.5 shows the distributions of X and Y at time $T = 200$ for

Figure 3.4: **Model 1: Open-Access Vessel Dynamics with Confidence Interval, Adjustment Parameter (a)n = 10^{-1} and (b) n = $5 \cdot 10^{-1}$ (c = 1,189,565 NOK, p = 2 NOK/kg).**

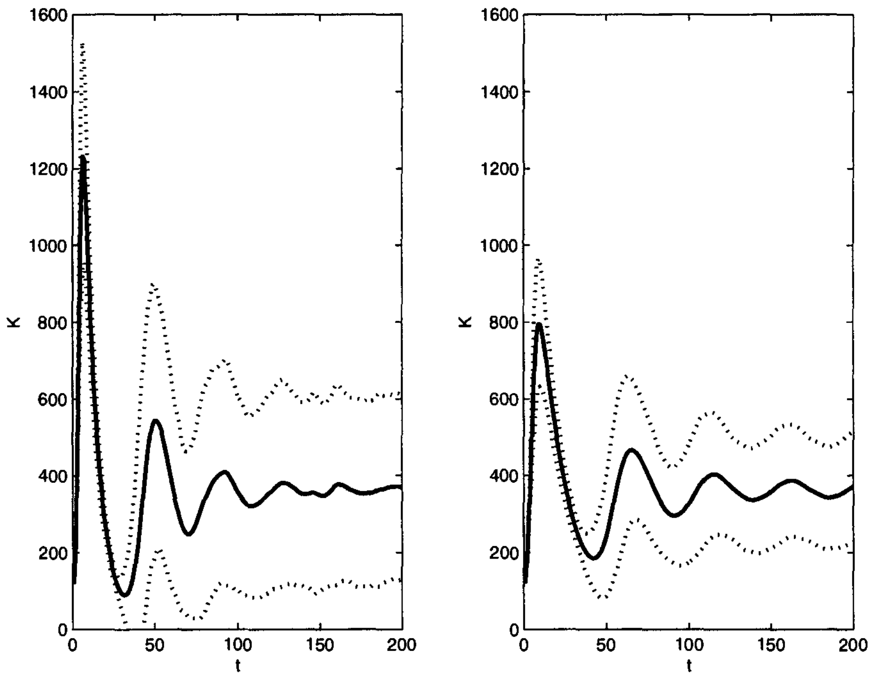
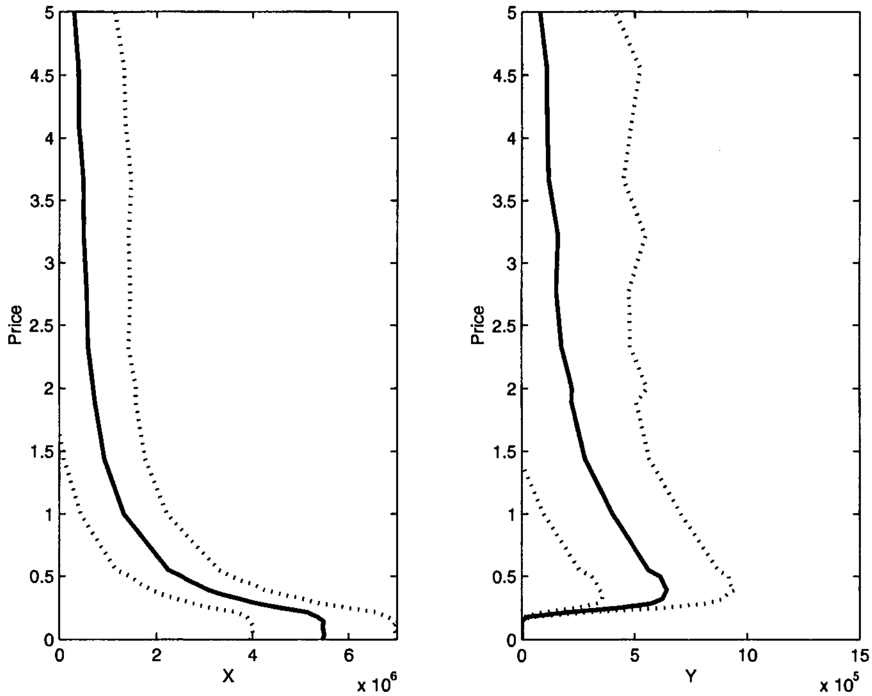


Figure 3.5: **Model 1: Open-Access Stock and Harvest at Time t=200 with Confidence Intervals (c = 1, 189, 565 NOK).**



different prices. For the stock, zero is within one standard deviation from the mean if price is above 1.7 NOK/kg. Although X never reaches zero (unless $p \to \infty$), it gets so close that the stock virtually has gone extinct even for the prices shown in this figure. The harvest curve can be regarded as a stochastic equivalent to the backward-bending open-access supply curve described by Copes (1970) and estimated for the North Sea herring fishery by Nøstbakken & Bjørndal (2003).

3.3.2 Model 2: The Cobb-Douglas Production Function

The optimally regulated and the open-access fisheries will now be analysed when production economics are explained by the Cobb-Douglas function.

The Optimal Linear Feedback Policy

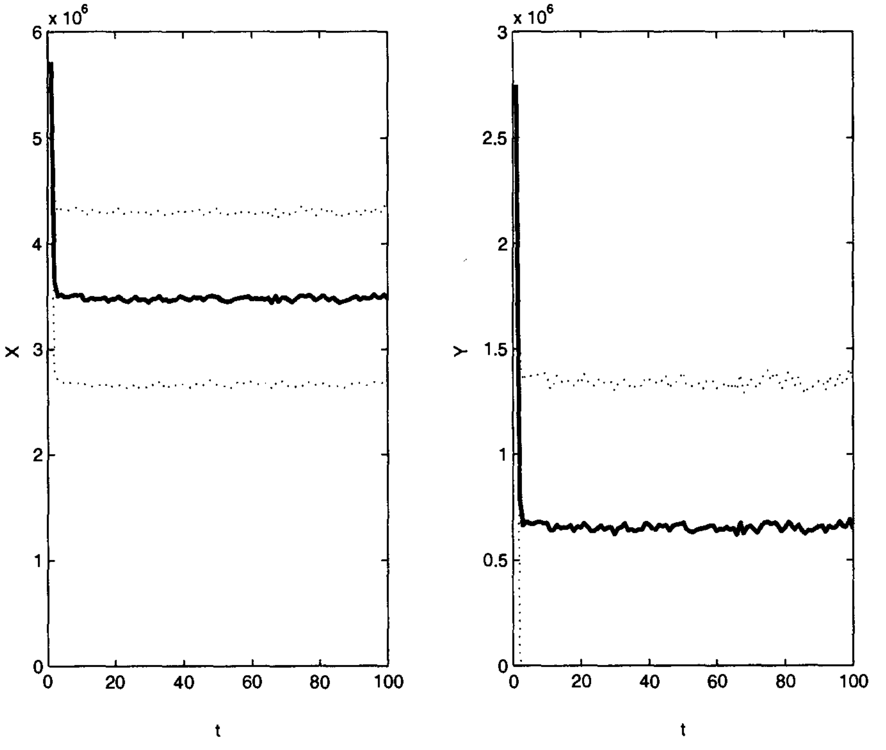
Optimal linear feedback policies (equation 3.14) are approximated by stochastic simulations for different prices keeping other parameters constant. These feedback rules are then applied to the dynamic model of the North Sea herring fishery, which are simulated $N = 1,000$ times over $T = 100$ years. Initial biomass is set to L.

If price is too low, i.e., less than about 0.1 NOK/kg, harvesting is not profitable at any stock level and both α and β in the linear feedback equation (3.14) are zero. However, for prices above this level, the optimal linear feedback seems to be rather insensitive to changes in price (and cost). The simulation results show that the optimal β stays very close to 1 although it is decreasing in price. Optimal α increases with price, but the relative change in α is small. For price $p = 2$, the optimal linear feedback policy is approximately $Y_t = -2,850,000 + 0.99X_t$. For positive values of X_t, harvest never equals total stock and extinction of the stock is therefore never optimal when $p = 2$. Recall from section 3.2.2 the "common sense" condition for harvest $0 \leq Y_t \leq X_t$. We have already established that the above feedback policy ensures that $Y_t < X_t$. From the condition $Y_t \geq 0$ we thus get the following optimal (linear) feedback policy for the North Sea herring fishery ($p = 2$):

$$Y_t = \begin{cases} 0 & \textit{if} \quad X_t < 2,880,000 \\ -2,850,000 + 0.99X_t & \textit{otherwise} \end{cases} \tag{3.17}$$

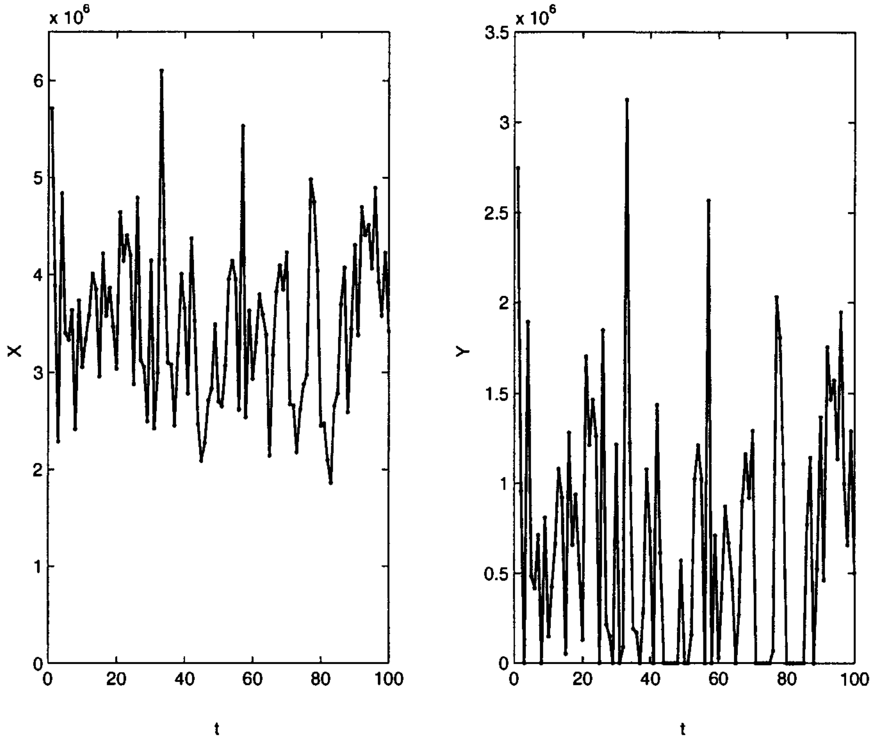
Figure 3.6 shows the simulation results for price $p = 2$ based on the feedback policy given by equation (3.17). After a transition period, the mean values of biomass and harvest level out at about 3.5 million tonnes and 654,000 tonnes, respectively. These values are close to the maximum sustainable yield levels of biomass and harvest (cf. section 3.2.3). If we, however, look at individual realisations, we see that harvest changes from zero in some periods to very high catches in other periods. The linear feedback rule thus appears to lead to pulse fishing in this case. This is illustrated in Figure 3.7, where one realisation of stock and catch dynamics

Figure 3.6: **Model 2: Optimal Management Stock and Catch Dynamics with Confidence Intervals (c = 1,189,565 NOK, p = 2 NOK/kg, $\delta = 0.06$).**



is shown.

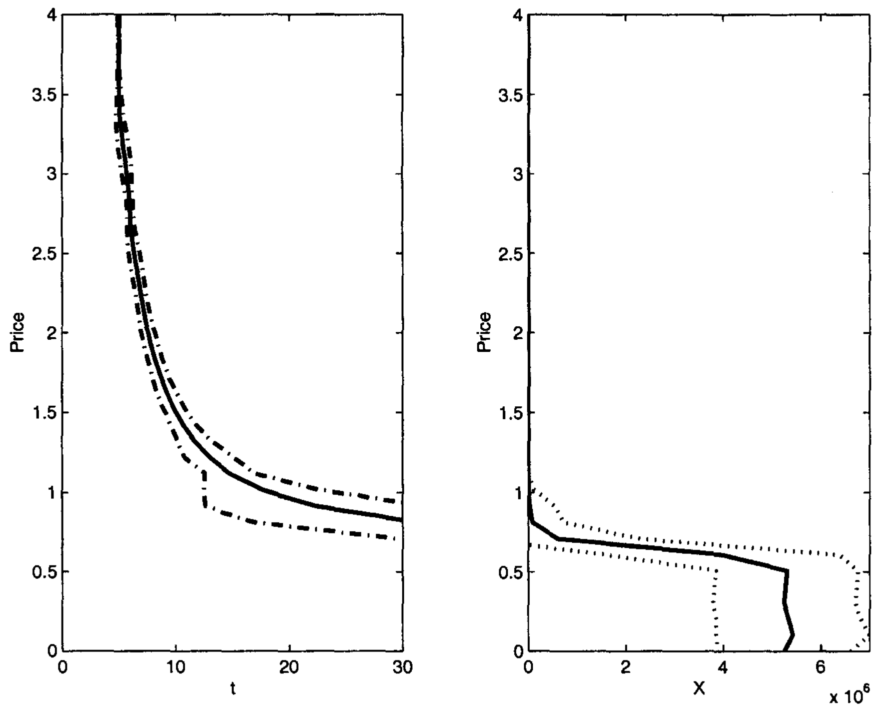
Figure 3.7: **Model 2: Optimal Management Stock and Harvest Realisations (c = 1,189,565 NOK, p = 2 NOK/kg, δ = 0.06).**



The Open-Access Fishery

Stochastic simulations of the open-access fishery result in depletion of the fish stock in all the $N = 1,000$ simulations (before time $T = 100$) given that price is above a minimum level that makes fishing viable in the first place. Initial biomass and number of vessels were set to L and 120, respectively. Bjørndal & Conrad (1987b) studied the dynamics of the North Sea herring fishery using a deterministic model and the Cobb-Douglas production function used here. They concluded that the likelihood of overshooting and possible extinction under open access is greater with discrete adjustments. Incorporating uncertainty into the stock-recruitment relationship, as has been done here, further increases the likelihood of overshooting compared to the deterministic case.

Figure 3.8: **Model 2: Open Access Time of Extinction and Biomass at Time t=100 with Confidence Intervals (c = $1,189,565$ NOK).**



Time of total extinction of the fish stock with confidence levels are shown in Figure 3.8a for different prices. If price is above 1.1 NOK/kg, it is very likely that the stock will go extinct within 30 years under an open-access regime. The variance in time of extinction is very small for prices above 1.2 NOK/kg. In these cases, the simulation results imply that the stock will go extinct after five to ten years. Figure 3.8b shows biomass at time $T = 100$ for different prices.

Time of extinction is influenced by the initial values of biomass and number of vessels used in the numerical analysis. As in the open-access case for Model 1 (Spence production function), there is a very large increase in number of vessels from the first to the second time period because of high net revenues in the first period resulting from the initial values of K and X. The choice of initial values does however not affect the conclusion that the stock eventually goes extinct under an open-access regime as long as price is above 1.1 NOK/kg.

3.3.3 The North Sea Herring Fishery 1981-2001

In the following sections, Models 1 and 2 are used to simulate harvest of North Sea herring, 1981-2001, under open access and optimal management. Average prices and variable costs for these years obtained from the Norwegian Directorate of Fisheries are used. The simulation results will be compared to the actual harvest policies for the North Sea herring fishery.

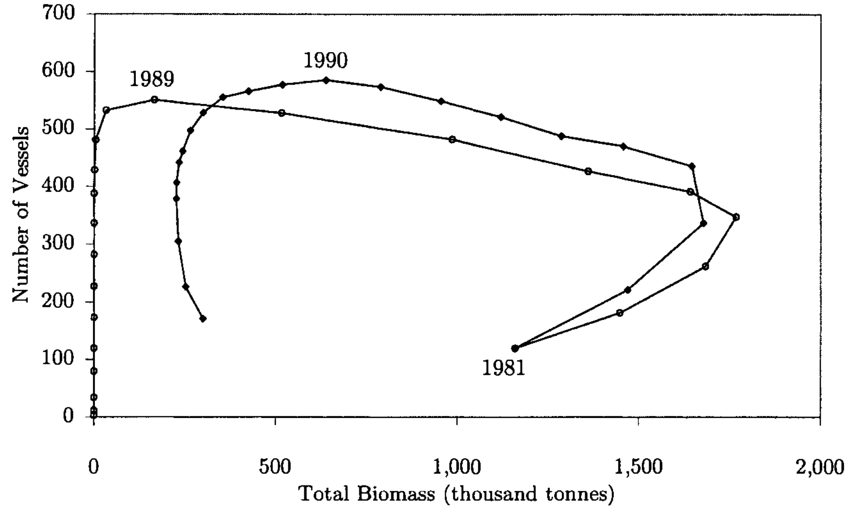
Open-Access Dynamics

We start out by simulating the open-access dynamics of the North Sea herring fishery, 1981-2001. Initial biomass in 1981 was, according to ICES, 1,160,300 tonnes. Initial number of vessels is set to 120.

The simulation results from the $N = 1,000$ simulations show that in Model 2 (Cobb-Douglas production function) the stock would go extinct after about 10 years (1990). The corresponding prediction when using Model 1 is, as expected, that the stock would not have gone extinct. Recall that when using the Spence production function, price has to approach infinity for the stock to go extinct. As a result, the number of vessels and harvest decrease steadily until the stock eventually starts increasing again. Full depletion is within one standard deviation from the average stock level from 1996 onwards. In Model 2, the same is true from 1988 onwards.

Figure 3.9 shows open-access dynamics in terms of number of vessels and stock levels for the two models. By comparing vessel dynamics, we see that the number of vessels reaches its maximum in 1990 in Model 1 and in 1989 in Model 2. Until 1984-1985 the models appear to be somewhat similar. From this point onwards, however, the two models' predictions are quite different. In both models the number of vessels is increasing while stock levels are decreasing. The approximate change in number of vessels is from 400 to 550 in Model 1 and from 440 to 600 in Model 2. The corresponding change in biomass is from 1,650 thousand tonnes to 640 and 160, respectively. While this change only takes four years in Model 2, the

Figure 3.9: **Open-Access Dynamics, 1981-2002: Model 1 (•) (Spence) and Model 2 (Cobb-Douglas).**



same process takes about six years in Model 1.

To answer the question whether open access could lead to stock extinction, one would get very different conclusions depending on which model specification one uses. Both the Spence and the Cobb-Douglas functions fit the data (Bjørndal & Conrad, 1987b). It is difficult to say which of the two models offers the best description of the harvest relationship in the North Sea herring fishery. The fishery has not been unregulated since the 1970s.[11] We therefore have no real observations to compare the simulation results to.

[11]See Nøstbakken & Bjørndal (2003) on regulations of the North Sea herring fishery 1981-2001.

The choice of model (Cobb-Douglas or Spence production functions) does not have a big impact on predictions if the stock level is not very low. In periods when the stock is close to zero, however, the two models give very different predictions. The models' predictions for periods when the stock is close to total extinction should therefore be evaluated when determining what production function to use when modelling the North Sea herring fishery. When the North Sea herring fishery was closed in 1977, the stock level was close to extinction. It is possible that the moratorium saved the stock from going extinct as put forward by Bjørndal & Conrad (1987b). This would suggest that the Cobb-Douglas function best describes the fishery. However, since the stock never has gone extinct, it could very well be possible that the Spence production function gives a better description of harvest in the fishery. In that case, we have seen that open access would not have resulted in total depletion of the North Sea herring stock.

Optimal Management

We now compare the performance of the optimal harvest policies, in terms of annual harvest and revenues, to the actual harvest of North Sea herring over the period 1981-2001. To make the comparison fair, the size of the environmental shock in each period (z_t) is calculated based on the estimated stock-recruitment function and actual stock levels: $z_t = \frac{X_t}{\hat{X}_t} = \frac{X_t}{G(S_{t-1})}$.

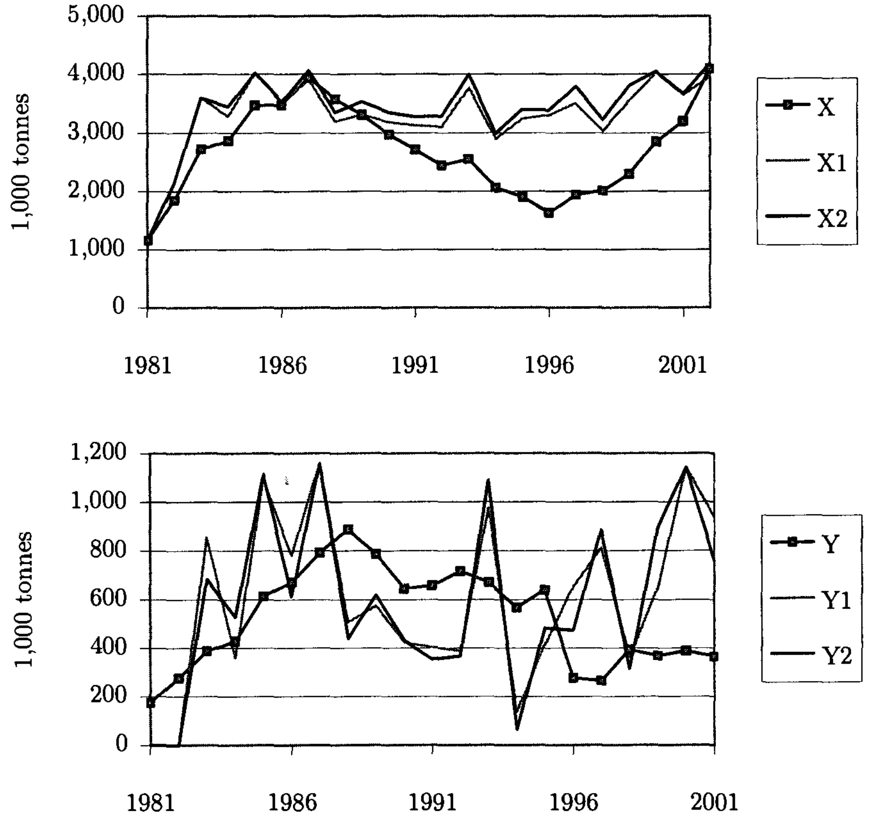
In the previous sections, we found that the choice of harvest relationship used in the bioeconomic model (Spence or Cobb-Douglas) was critical for the predicted open-access dynamics. This, however, does not seem to be important when determining optimal harvest for the period 1981-2001. Both annual harvest and stock levels are almost identical in the two models, as can be seen in Figure 3.10. The actual harvest and stock, on the other hand, deviate from the optimal policies.

According to both our models, optimal management implies that the moratorium should not have been lifted in 1981 - the fishery should on the contrary have stayed closed until 1983. This would have rebuilt the stock to a level of some three million tonnes where the stock subsequently levels out. Remember that the total biomass that corresponds to MSY according to our estimates is about 3.52 million tonnes. Expected optimal harvest would therefore have been close to MSY.

Harvest under the optimal management policies fluctuates significantly with annual harvests between a high of 1,160 thousand tonnes in 1987 and a low of 105 thousand tonnes in 1994. These fluctuations follow the fluctuations in z. The optimal escapement level changes some from year to year as prices and costs change. The environmental shocks, however, are what cause most of the fluctuations in optimal harvest (Y1 and Y2) in Figure 3.10.

In spite of the fact that total landings were above optimal harvesting levels in the early 1980s, total biomass grew steadily until it reached 3.94 million tonnes in 1987. This is very close to the optimal stock size in

Figure 3.10: **Optimal Policies, 1981-2002: Models 1 (Spence) and 2 (Cobb-Douglas) versus Actual Policy; Stock Levels (top) and Annual Catches (bottom), $\delta = 0.06$.**



1987. One explanation for this rather large increase in actual biomass is the substantial positive environmental shocks in the early 1980s. From 1987 until 1996, however, the North Sea herring stock showed a declining trend. During this period the actual harvest policy was undoubtedly suboptimal. From 1997 onwards, quotas have been small to allow the stock to grow. The stock in 2003 was about 4.32 million tonnes according to ICES (2003). The stock has thus been allowed to grow to a level far above what maximises net revenues from the fishery.

Figure 3.11: **Sum of Present Value of Revenues from 1981 Onward.**

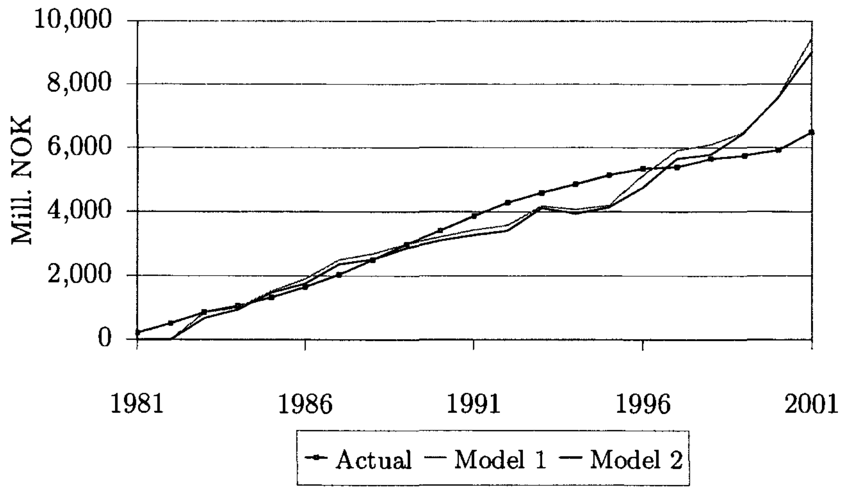


Figure 3.11 shows sum of present value of net revenues from 1981 onwards for the two optimal harvest policies and actual harvest.[12] The two optimal harvest policies derived from the bioeconomic model give al-

[12]The sum of present value of net revenues for year t is defined as: PV_t =

most the same net revenues, although the optimal escapement policy from Model 1 (Spence) results in marginally higher discounted net revenues. The gap between the accumulated discounted revenue lines for the two optimal policies is not constant. It increases in some years and decreases in other years, meaning that the constant escapement policy performs best in some periods, while the linear feedback policy is better in other periods.

The actual policy has the highest present value of revenues for the periods 1981 through 1984 and 1981 through 1996. However, while the stock level under optimal management would have been 3.3-3.4 million tonnes in 1996, the stock level under the actual regulations was only 1.6 million tonnes. It is therefore not correct to say that the actual management (1981-1996) was better than the optimal harvest policies. Furthermore, for the whole period, 1981-2001, the two optimal policies clearly outperform the actual harvest policy. As can be seen in Figure 3.10, the actual stock level (X) equals the optimal stock levels (X1 and X2) in 2002. When comparing present value of revenues from 1981 to 2001, the three policies - Model 1, Model 2, and actual - have the same initial stock in the first year and virtually the same escapement in the last year. Comparing policies over this period should therefore be reasonable.

The optimal policy from Model 2 (Cobb-Douglas) is, as discussed earlier, the optimal feedback policy among *linear* policies. The linear feedback

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$\sum_{s=1981}^{t} (1+\delta)^{t-s} R_s$, where R_s is net revenues in year s, and δ is the discount rate.

policy can be the best of all possible policies. There might, however, be non-linear feedback policies which outperform the optimal linear policy. Nevertheless, the fact that the linear feedback policy gives almost the same results as the optimal escapement policy (Model 1) indicates that a linear feedback probably is a close approximation of the optimal policy.

In this section we have seen that the difference in optimal annual harvest levels is very small when modelling the North Sea herring fishery with a Spence production function compared to a Cobb-Douglas production function. This result is contrary to what we found when analysing open-access dynamics. The fact that the two harvest relationships give so similar recommendations for optimal harvest of North Sea herring strengthens the robustness of these policies.

3.4 Summary and Conclusions

In this paper, a stochastic model has been used to analyse the management of North Sea herring. Looking at stock-recruitment data for the North Sea herring fishery, it is obvious that there are fluctuations that cannot be explained in the standard deterministic bioeconomic models. These fluctuations have been treated as environmental shocks occurring after harvesting in one period, but before determining harvest quotas in the next period.

Two different production functions have been used in the analysis. The long-term supply in an open-access fishery was seen to be positive when using the Spence production function, given that price is high enough for fishing to be viable. We found that the corresponding result when using the Cobb-Douglas production function was total extinction of the fish stock and consequently no harvesting in the long run. Herring prices are and have been more than high enough for the stock to go extinct if the fishery is left unregulated (Cobb-Douglas). Although the results in terms of expected long-term harvest are very different between the two models, predicted harvest in periods when biomass is not close to extinction was found to be quite similar when comparing the models.

In an optimally regulated fishery, the Spence production function gives us a constant-escapement rule, as proved by Reed (1979). The optimal escapement level was seen to decrease with price. For the model based on the Cobb-Douglas production function, the analysis was limited to finding optimal *linear* feedback policies for the fishery. The optimal linear policy was fairly insensitive to changes in price. We found that the linear feedback can lead to pulse fishing. The optimal policies for the two harvest functions were seen to be very similar when applying them to the North Sea herring fishery, 1981-2001. This indicates that the optimal feedback policy when using a Cobb-Douglas function is not very different from our linear feedback rule. This result also confirms that as long as the stock is close to MSY, or not too close to extinction, the sensitivity of the results to the choice of production function in the model is modest.

The North Sea herring fishery was closed in 1977 to allow the stock to recover after being severely depleted in the 1960s and 1970s. The moratorium was lifted in 1981 in the southern part of the North Sea and in 1983 in the northern part. We have tried to evaluate the actual management of the North Sea herring fishery from 1981 through 2001. According to our analysis, optimal management of the North Sea herring would have implied that the fishery stayed closed until 1983. While quotas were found to be too high in the first part of the 1981-2001 period, the problem in the last part of the period seems, on the contrary, to be that quotas have been set too low.

Our analysis confirms the conclusion made in Nøstbakken & Bjørndal (2003) that the regulatory regime can have a substantial impact on the supply of North Sea herring. The difference in expected long-run supply between open access and optimal management depends on the harvest function used, but is nevertheless considerable. Optimal management results in expected annual landings close to the maximum sustainable yield of 660 thousand tonnes. Under open access, the long-run equilibrium stock and harvest can be zero (Cobb-Douglas) or close to zero (Spence). These results are similar to Nøstbakken and Bjørndal's (2003) results for the deterministic case.

This paper represents a continuation of the work in Nøstbakken & Bjørndal (2003). The current analysis can be extended in several ways. One possibility would be to introduce measurement error in the stock estimates (cf. Clark & Kirkwood, 1986). This would also allow for an analysis of optimal management instruments (cf. Weitzman, 2002), and an analysis of how different management instruments affect the supply of herring. Another possibility would be to explore implications for optimal management of having autocorrelated instead of independent and identically distributed environmental shocks. The analysis could be extended further by combining the supply curves with estimations of demand curves in order to study the market for North Sea herring.

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Chapter 4

Regime Switching in a Fishery with Stochastic Stock and Price

Abstract

We develop a bioeconomic model of a fishery subject to stock uncertainty and price uncertainty. With a linear control model, the optimal harvest policy is a bang-bang approach to the optimal stock level, where one harvests either at minimum or full capacity. It is assumed that changing the harvest rate is subject to a switching cost. In this case we show that there are two switching curves in stock-price space, one for entering and one for leaving the fishery. Numerical methods are used to characterize the optimal switching policy for the fishery.

4.1 Introduction

Over the last couple of decades there has been an increase in the application of stochastic bioeconomic models in the literature with prices, biological parameters, etc. fluctuating according to stochastic processes. Whereas the literature contains numerous studies of the management of natural resources under some kind of uncertainty, most of them only analyse how one source of uncertainty influences the bioeconomic model. Few studies consider the effects on optimal management of several sources of uncertainty that simultaneously affect different parts of the bioeconomic model.

The purpose of this study is to analyse how uncertainty in stock growth and price influence the optimal harvest of fish. We build our model on the well-known deterministic linear-control model presented by Clark & Munro (1975). When the stock reaches the critical level, harvest is set at some interior value, which maintains the optimal stock level (steady state). Uncertainty is incorporated into the model by letting price and stock-recruitment evolve according to known stochastic processes. The Clark-Munro model is further extended by introducing switching costs. It seems reasonable to assume that increasing and/or decreasing the harvest rate incurs certain costs. We therefore assume lump-sum switching costs of changing the harvest rate. It will be shown that the optimal harvest is either to harvest at minimum or full capacity. While it is not possible to find a closed form solution to the optimisation problem, numerical methods can be used to approximate the solution. These will be used to characterise the optimal policy, which is defined by regime-switching curves in stock-price space; one for activating the fishing fleet and one for withdrawing the fleet from the fishery.

Of related work, Clarke & Reed (1989) and Reed & Clarke (1990) introduced price and growth uncertainty in a forest harvest model, modelling the price process as geometric Brownian motion and assuming stock growth to be age or size dependent. Brennan & Schwartz (1985) present a model where a project, a mine is used as an example, can operate in two modes; active or passive. There is one output, and the output price fluctuates according to a known stochastic process. The payoff from the project depends on the current output price and on the choice of output rate. Switching between the active and the passive modes is done at a fixed cost. Brennan and Schwartz are able to derive expressions for the value of the project. They also consider optimal management of the mine. In his study of entry and exit decisions under uncertainty, Dixit (1989) builds on the analysis in Brennan & Schwartz (1985). Dixit makes several simplifications to the Brennan and Schwartz model, such as assuming a fixed production rate in the active state. This allows him to derive analytical results. In a recent work, Lumley & Zervos (2001) analyse optimal investment in a non-renewable natural resource industry subject to switching costs.

The theory on real options has been developed over the past two decades. Real option theory involves treating investment projects as options to invest, and the investment projects can be anything from job search or whether to open a factory, to the exploitation of natural resources. Financial economics offer techniques to price options and to determine optimal exercise time or state. The real options approach is therefore a convenient way to analyse investment projects and is especially valuable when analysing projects involving uncertainty. The literature on real options contains many examples of optimal switching models. Dixit & Pindyck (1994) give a good introduction to real options and they present several models of optimal switching. Other examples of optimal switching models can be found in Trigeorgis (1996), and in the recent collection of Schwartz & Trigeorgis (2001).

The remainder of the paper is organised as follows. The next section specifies the bioeconomic model. The numerical analysis, where we characterise the optimal policy, is presented in section 4.3. A summary and conclusions are presented in section 4.4.

4.2 Model Specification

Let the fish stock at instant t be denoted by $X = X(t)$, where time is continuous, with $\infty > t \geq 0$. Instantaneous harvest from the stock, the harvest rate, is denoted by $Y = Y(t)$. There is an upper limit to how much the fishing fleet can harvest at every instant of time given by the maximum harvest rate $Y_{\max}$. We therefore have $Y_{\max} \geq Y \geq 0$. We assume the dynamics of the resource stock X is given by:

$$dX = [F(X) - Y]\,dt + \sigma_X X dz_X, \tag{4.1}$$

where $F(X)$ is a strictly concave growth function, with $F(0) = F(K) = 0$ and where $K > 0$ is the carrying capacity of the environment. The term $\sigma_X X dz_X$ represents the stochastic part of the stock-growth relationship and can be thought of as random environmental fluctuations. $\sigma_X X$ is the standard deviation rate, $\sigma_X > 0$, $dz_X = \epsilon(t)\sqrt{dt}$, where $\epsilon(t)$ is a standard normal, iid, random variable. It follows that $z(t)$ is a Wiener process. Clark & Munro (1975) explain growth by an equation similar to the deterministic part of equation (4.1).

The price of the resource, P, is assumed to follow a process of geometric Brownian motion (GBM), given by:

$$dP = \mu P dt + \sigma_P P dz_P, \tag{4.2}$$

where $\mu \geq 0$ is the drift rate and $\sigma_P P$ is the standard deviation rate, $\sigma_P > 0$. $dz_P = \epsilon(t)\sqrt{dt}$ is also an increment of a Wiener process. We further assume that $E\{dz_X, dz_P\} = 0$, i.e., we are dealing with a small fishery whose harvest has no affect on the world price, P. A positive drift rate implies that prices are increasing over time, perhaps reflecting a growing demand for fish protein or a decline in stocks, world-wide.

We make the standard assumption that an agent seeks to maximise the expected present value of net revenues from the fishery over an infinite horizon subject to the dynamic constraints given by equations (4.1) and (4.2).[1] Assume the cost per unit fish harvested is $c(X)$, with $c'(X) < 0$ and $c''(X) > 0$. If there is no uncertainty, i.e., if $\sigma_X = \sigma_P = 0$, and if the price is constant ($\mu = 0$), the model is exactly the same as the Clark-Munro model (1975). The optimal control problem is

$$J(X, P) = \max_{\{Y\}} E\{\int_s^\infty (P - c(X))Ye^{-\rho t}dt\}, \tag{4.3}$$

where ρ is the discount rate, subject to (4.1) and (4.2). The optimal harvest will therefore, at every instant of time, follow the most rapid approach path (MRAP) toward the optimal stock level. The optimal harvest is consequently either $Y = 0$ or $Y = Y_{\max}$. In the deterministic case ($\sigma_X = \sigma_P = 0$) with constant price, the optimal harvest rate is a bang-bang approach to the optimal stock level, then a constant harvest rate to maintain the optimal steady state.

We will assume that a switching cost is incurred for any change in harvest rate. The cost of increasing the harvest rate is A_{12} and the cost of decreasing the harvest rate is A_{21}. This changes the original problem and one might question if the MRAP solution is still optimal. Let ϵ_i and τ_j,

[1]Fixed costs are disregarded as we assume the fleet in question participates in other, and to the fleet, more important fisheries.

where $i = 1, ..., n$ and $j = 1, ..., m$, be the times of increases and decreases in harvest rate, respectively. The net present value of the cost of the $n + m$ changes in harvest rate must now be subtracted from the expression given by equation (4.3). The control problem is nevertheless still linear in harvest and is therefore maximised by the MRAP solution. Any approach other than bang-bang lowers the expected discounted value of net revenues. This implies that as long as it is optimal to vary the harvest rate at all, it is optimal to switch between zero and $Y_{\max}$ since the cost of doing so is the same as the cost of switching between interior harvest rates ($Y_{\max} > Y > 0$). Hence, the MRAP solution maximises the expected value of the fishery subject to switching costs if the MRAP solution is also better than harvesting at a constant harvest rate at all times. This is what we investigate next.

Let the fishery be partially open at all times with a fixed harvest rate of $mY_{\max}$ ($1 > m > 0$). By choosing this strategy switching costs are avoided. The corresponding stochastic control problem can be expressed as

$$J(X, P) = \sup_{m} E\left\{ \int_{s}^{\infty} (P - c(X))\, mY_{\max} e^{-\rho t} dt \right\}, \tag{4.4}$$

where $dX = [F(X) - mY_{\max}]dt + \sigma_X X dz_X$, while dP as before is given by equation (4.2). The Hamilton-Jacobi-Bellman equation for the problem stated in equation (4.4) is

$$\rho V = \sup_{m} \Big\{ (P - c(X))mY_{\max} + (F(X) - mY_{\max})V_X + \mu P V_P + \tfrac{1}{2}\sigma_X^2 X^2 V_{XX} + \tfrac{1}{2}\sigma_P^2 P^2 V_{PP} \Big\}.$$

The maximum condition for the problem is

$$\frac{\partial\{\cdot\}}{\partial m} = (P - c(X) - V_X)Y_{\max} = 0,$$

and we see that the supremum cannot be reached for any value of m. This implies that the optimal solution to the profit maximisation problem is a bang-bang solution. The optimal harvest rate is consequently either $Y = 0$ or $Y = Y_{\max}$ and we can define two regimes; $R = 1$, inactive, and $R = 2$, active (harvesting at the rate $Y = Y_{\max}$).[2]

Brekke & Øksendal (1994) characterise the solution of a switching model, which encompasses the current one. Using stochastic calculus, they derive conditions for the optimal solution to the problem and prove the existence of a solution. The optimal value function $V(X, P, R)$ for the

[2]Since it could become optimal to harvest the stock to extinction the harvest rate is also limited by the available stock, i.e., $Y = \{0, \min(Y_{\max}, X)\}$.

fisheries management problem must satisfy.[3]

$$\begin{aligned}\rho V(X,P,R) &\geq \pi(X,P,R) + [F(X) - Y]\, V_X(X,P,R) \\ &+ \mu P V_P(X,P,R) + 0.5\sigma_X^2 X^2 V_{XX}(X,P,R) \\ &+ 0.5\sigma_P^2 P^2 V_{PP}(X,P,R)\end{aligned} \tag{4.5}$$

and the condition

$$V(X,P,R) \geq V(X,P,i) - A_{Ri}, R \neq i, \tag{4.6}$$

where $R \in (1,2)$ is regime, and $\pi(X,P,R) = [P - c(X)]Y_{\max}(R-1)$ is the flow of net revenues per unit of time from harvesting the stock in regimes 1 and 2. The left-hand side of equation (4.5) is the fishery's opportunity cost in regime R, while the right-hand side, which gives the sum of instantaneous net revenues and value gain from changes in price and stock, is the return rate in regime R. The condition given by equation (4.6) states that the value of remaining in regime R must be at least as high as the value of regime switching, given by the value of being in the other regime minus the cost of switching. In addition to the conditions given by equations (4.5) and (4.6), the optimal value function must satisfy some regularity conditions, namely the value matching and smooth pasting conditions. These

[3] Dixit & Pindyck (1994) provide necessary and sufficient conditions to similar real options problems.

regularity conditions are given by equations (4.7) and (4.8), respectively.

$$\begin{aligned} V(X_{entry}, P_{entry}, 1) &= V(X_{entry}, P_{entry}, 2) + A_{21} \\ V(X_{exit}, P_{exit}, 2) &= V(X_{exit}, P_{exit}, 1) + A_{12} \end{aligned} \tag{4.7}$$

$$\begin{aligned} V_X(X_i, P_i, 1) &= V_X(X_i, P_i, 2), \ \ for \ \ i = \{entry, exit\} \\ V_P(X_i, P_i, 2) &= V_P(X_i, P_i, 1), \ \ for \ \ i = \{entry, exit\} \end{aligned} \tag{4.8}$$

The optimal policy can be defined by switching curves in stock-price space. If $A_{12} > 0$ and/or $A_{21} > 0$, there are two switching curves in $X - P$ space; one for entering the fishery (moving from regime 1 to regime 2) and one for leaving the fishery (moving from regime 2 to regime 1). The switching curves are implied by equations (4.5) and (4.6). In regime 1, one is indifferent between entering the fishery and staying inactive if $V(X, P, 1) = V(X, P, 2) - A_{12}$. This defines the entry curve. Similarly, in regime 2 one is indifferent between leaving and staying active if $V(X, P, 2) = V(X, P, 1) - A_{21}$, which defines the exit curve. Between the two switching curves both harvesting and inactivity can be optimal depending on what one is currently doing; the optimal behaviour is to remain passive. The higher the switching costs, the larger the area between the switching curves and the less frequent would be switches by the fleet. If $V(X, P, 1) > V(X, P, 2)$, inactivity is always optimal, whereas if $V(X, P, 1) < V(X, P, 2)$ it is always optimal to harvest. Dixit (1989) describes how the presence of uncertainty and switching costs can result in hysteresis, which he defines as "the failure of an effect to reverse itself as its underlying cause is reversed". This inertia explains why there are two switching curves in $X-P$ space and not one as would be the case in a fishery without switching costs. In the next section numerical methods are used to approximate optimal switching curves for the fishery.

4.3 Numerical Analysis

The optimality conditions, along with regularity conditions can be used to numerically approximate the optimal switching curves for the problem. In this section we first study the long-run distribution of biomass when there is no harvesting. Next, optimal switching curves for the fishery are approximated and the optimal management fishery is simulated and characterised.[4]

Before we can initiate the numerical analysis we need to make assumptions about the specific forms of the cost and growth functions and we must specify model parameters. First, we assume a cost per unit of harvest of $c(X) \equiv \frac{c}{X}$, a unit cost function which corresponds to the Schaefer production function and a constant cost of c per unit effort. Second, stock

[4]The numerical analysis utilises the CompEcon Toolbox (for Matlab) as developed by Miranda & Fackler (2002). The Matlab code used in this section can be made available by the author upon request.

growth is assumed to follow the logistic growth function $F(X) = rX(1 - \frac{X}{K})$, where r is the intrinsic growth rate. Parameter values are summarised in Table 4.1. Note that the maximum harvest rate is set to $Y_{\max} = 0.25$. This is above the maximum sustainable yield of $MSY = \frac{rK}{4} = 0.125$ and it is thus impossible to harvest at full capacity at all times without driving the stock to extinction. We assume no drift in the price of fish, i.e., $\mu = 0$. For most commercial fish stocks this seems to be a reasonable assumption. The assumption does however not affect our results in any significant way. The same is the case for the assumption of $A_{12} = A_{21}$; the equality is not necessary and does not qualitatively change the results.

Table 4.1: **Parameter Values**

Parameter	Value	Description
r	0.5	Intrinsic growth rate
K	1	Biological carrying capacity
c	0.25	Cost per unit effort
$Y_{\max}$	0.25	Upper bound harvest rate
μ	0	Price drift
σ_P	0.2	Price diffusion
σ_X	0.3	Stock diffusion
δ	0.1	Discount rate
A_{12}	0.01	Cost of increasing harvest rate
A_{21}	0.01	Cost of decreasing harvest rate

The long-run distribution of the pristine stock is found numerically using equation (4.1) with $Y = 0$, the logistic growth function, and parameter values as presented in Table 4.1.

Figure 4.1: **Long-Run Stock Density, Y = 0. Base case $\sigma_X = 0.30$ (solid line), $\sigma_X = 0.45$ (dash-dot line), and $\sigma_X = 0.15$ (dashed line).**

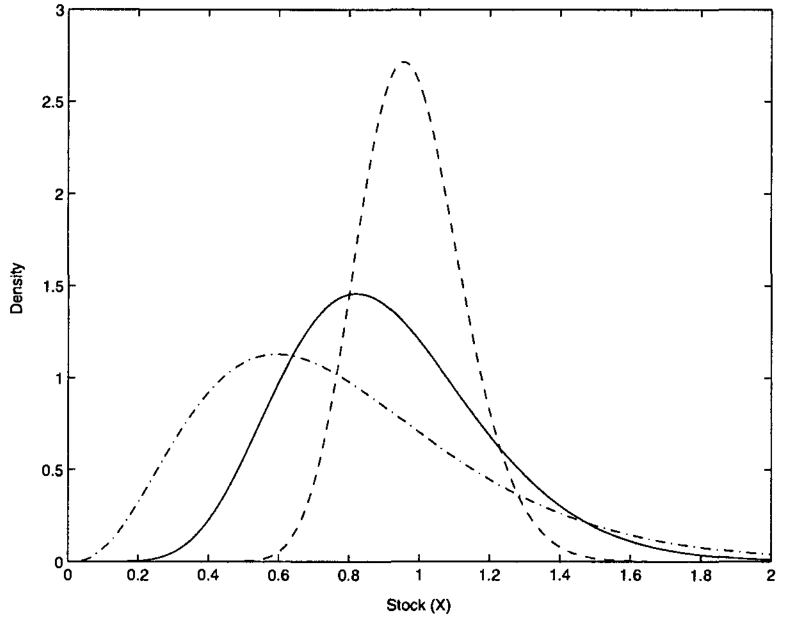


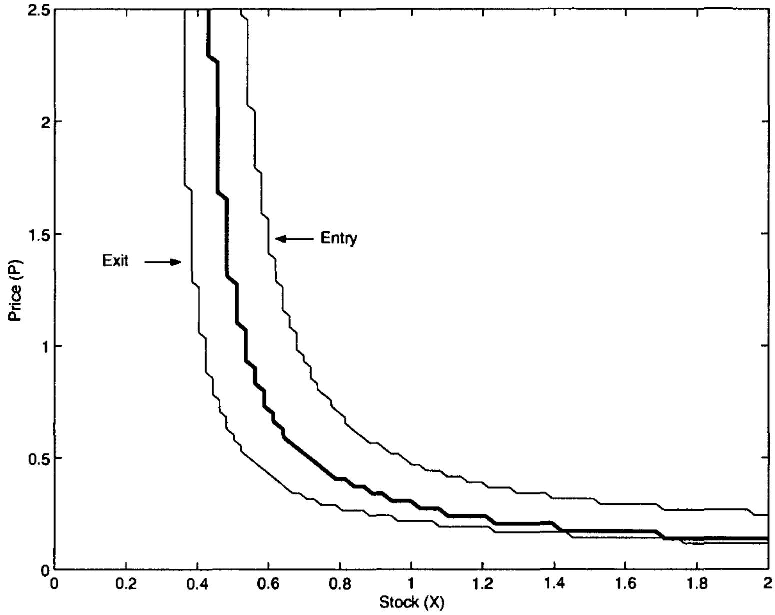
Figure 4.1 shows the long-run density functions for the base case ($\sigma_X = 0.3$) and for standard deviation rates 0.15 and 0.45. Dixit & Pindyck (1994) note that $EX = K(1 - \frac{\sigma_X^2}{2r})$. The stock density varies significantly with the value of the standard deviation rate σ_X. For $\sigma_X = 0.3$, the base case, the vast majority of stock realisations are within the interval 0.15 to 2, where 2 is twice the size of the carrying capacity. The stock can in theory go extinct even in the no-fishing case but the likelihood of this is approximately zero.

4.3.1 Optimal Switching Curves

Optimal switching curves for the fishery are found using a cubic spline approximation function. A spline can be described as any smooth function that is piecewise polynomial but also smooth where the polynomial pieces connect (see e.g. Judd, 1998). A cubic spline is constructed of piecewise third-order polynomials and produces continuous first and second derivatives. A Matlab procedure described in Fackler (2004) is used to obtain the numerical solution. The procedure uses function approximation and collocation to find the optimal solution characterised by the optimality conditions (4.5) and (4.6). In addition to these, we know that the fishery is valueless if the stock goes extinct and therefore add the condition $V(0, P, R) = 0$, which must hold for all P and R.

The approximate optimal switching curves can be seen in Figure 4.2. The two curves labelled entry and exit are the optimal switching curves in the base case (positive switching costs). The third curve in Figure 4.2 represents the case of no switching costs. The continuous state space must be discretised into a finite set of state nodes when approximating the optimal policy and this explains why the curves are not smooth. For X, 100 evenly spaced points on the interval $[0, 2]$ are used to make the grid of state nodes. Considering the long-run stock distribution (Figure 4.1), we see that the interval $2 \geq X \geq 0.15$ covers virtually every possible stock realisation. The long-run distribution of price, on the other hand, depends on initial price. For P, 100 evenly spaced points on the interval $[0, 2.5]$ are

Figure 4.2: **Approximate Switching Curves. Base Case (thin lines) and with No Switching Costs (thick line).**



chosen when defining the grid of state nodes.

Obviously, as price increases, it gets more and more profitable to harvest the stock, everything else being equal (Figure 4.2). The same is true as stock increases since the unit cost of harvesting is decreasing in stock size. Accordingly, it is always optimal to harvest when price is high and stock is high, while inactivity, or no harvest, is optimal if both variables are at low levels. In other cases the switching curves reflect the fact that there are trade offs between getting a high (low) price and having a low (high) stock. The sensitivity of the switching curves to changes in either of the two state variables decreases with the value of the state variable.

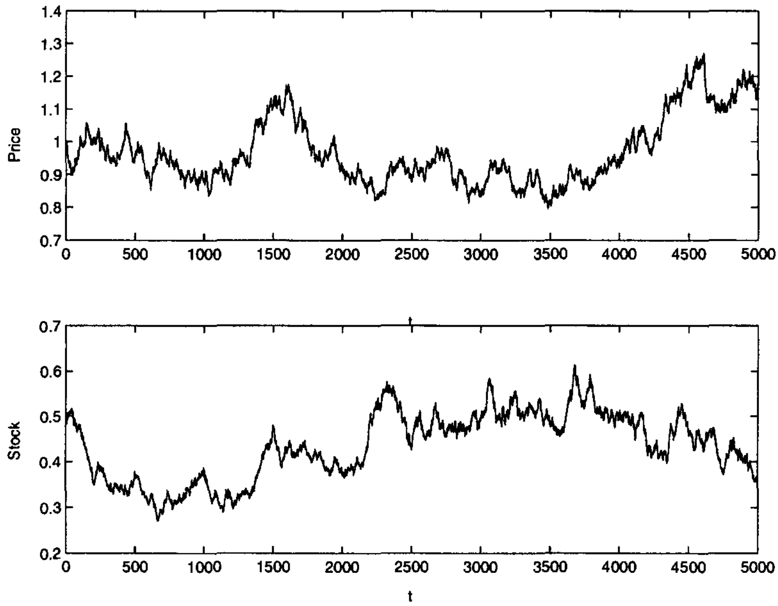
The switching curve representing entry into the fishery lies above the exit curve. It follows that there is an area between the two curves where fishing can be optimal or suboptimal, depending on the current regime. This is the band of hysteresis, as described earlier. The distance between the switching curves depends on the switching costs. If there are no switching costs there is only one curve, as can be seen in Figure 4.2. As the switching costs increase, the distance between the curves grows. Eventually, at very high switching costs, there will be no switching curves since no possible realisations of price and stock exist where harvest revenues would make up for the switching costs.

To our best knowledge, this is the first study of optimal switching curves in a fishery with stochastic stock and price.

4.3.2 The Optimal Management Fishery

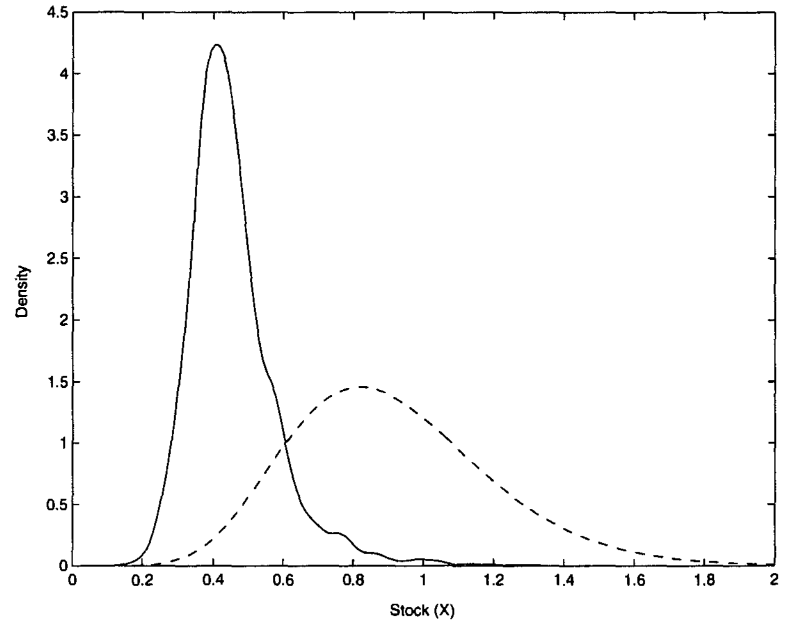
The long-run consequences of following the optimal switching policy are found by stochastic simulations. The policy given by the base-case switching curves described above are simulated 2,000 times over $T = 5,000$ time increments, where each time increment is set to $dt = 0.001$. Initial values of price and stock are 1 and 0.5, respectively. Sample realisations of price and stock are shown in Figure 4.3. The stock level is higher when the price is low than when price is high. This, of course, is because the stock is being harvested down whenever it is high enough to justify activating the fleet. The higher the price, the sooner activation becomes optimal. The long-run density of stock is shown in Figure 4.4 along with the density of the pristine stock.

Figure 4.3: **Sample Realisations of Price and Stock.**



According to the simulation results, a moratorium is in effect in the fishery most of the time. The average harvest at time increment T shows that a positive harvest rate (Y) is optimal only 45% of the time. The rest of the time the fishery is closed. A different choice of parameter values alters this. Nevertheless, the conclusion that the fishery stays closed a large share of the time does not come as a total surprise. Remember that we set the maximum harvest rate to Y_{max}. This is twice the maximum sustainable yield rate of 0.125. As a consequence it takes little time to harvest the

Figure 4.4: **Long-Run Stock Density: Optimal Policy and No Harvesting (dashed line).**



stock down from above the entry curve to below the exit curve. It can take considerably more time for the stock to grow back up to a level above the entry curve and as a result, the fishery is closed a large part of the time. What we find is referred to as pulse fishing in the literature (see e.g. Hannesson, 1975). Pulse fishing has been shown to be optimal in several cases where the control model is linear, i.e., when the cost of increasing capacity in the fishery is linear. If, on the other hand, we were dealing with a non-linear control problem, pulse-fishing would have been more surprising.

We set out to approximate optimal switching curves for the fishery and to study the implications of applying the optimal policy as defined by the switching curves. With this in place, we can analyse the sensitivity of the solutions to parameter changes. This is what we turn to next.

4.3.3 Sensitivity Analysis

We start out by evaluating the case analysed in Clark & Munro (1975). Steady-state conditions are easily derived for the deterministic case without fleet-adjustment costs. This case will therefore be used as a benchmark. We also analyse how changes in stock and price volatilities ($\sigma_i, i = X, P$) affect the switching curves, how sensitive the curves are to changes in growth rate, and finally, how changes in the maximum harvest rate affect the results presented in the previous section.

In the deterministic case with fixed price and no switching costs, there is an optimal steady-state stock level X^* realised at a certain harvest rate $Y^* \in [0, Y_{\max}]$. In steady state, harvest is set at some interior value which maintains the optimal stock level. Steady state stock and harvest rate are given by

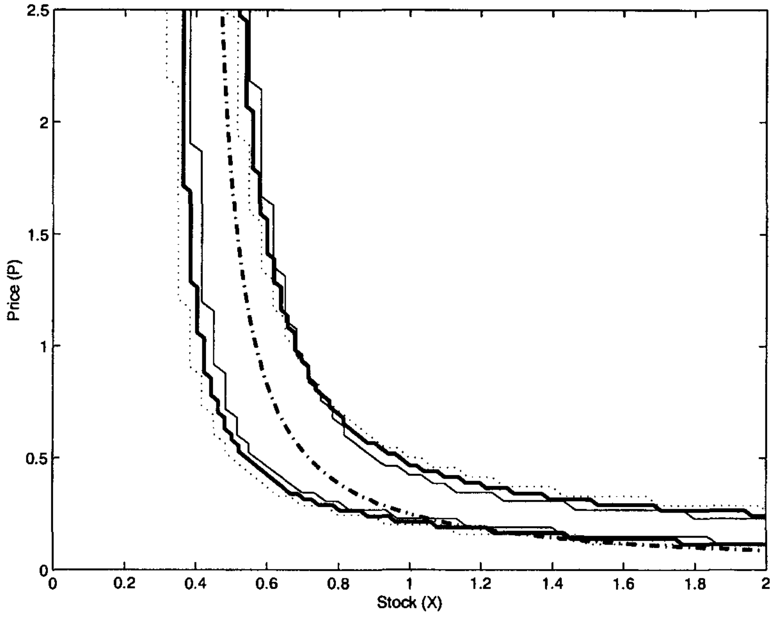
$$\begin{aligned} P - c(X^*) &= \frac{F(X^*)c'(X^*)}{F'(X^*) - \rho} \\ Y^* &= F(X^*). \end{aligned}$$

Based on the first equation we can calculate steady-state combinations of stock and price, which can be represented as a curve in stock-price space.

This curve is similar to the switching curves shown in Figure 4.2 for the stochastic case. If the fishery is not currently in steady state one should, depending on the current state, harvest either at Y_{max} or not at all until steady state is reached. In the deterministic case there will only be one switching curve even if fleet adjustments are subject to switching costs. When one knows everything there is no need to make fleet adjustments after the optimal steady state is reached. One will switch at most once and as a result the switching costs do not change anything.

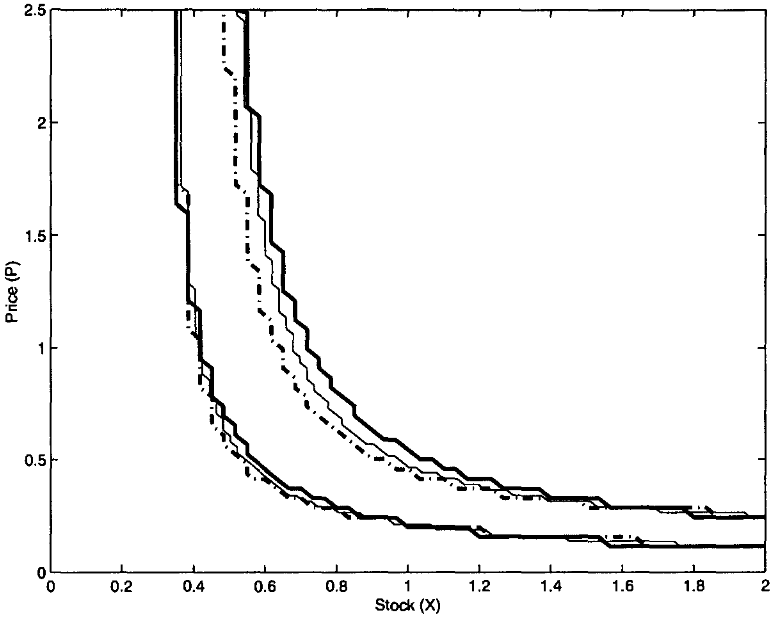
From the steady-state relationship we know it is not optimal to harvest at any positive, finite price for stock levels $X \leq (r-\delta)\frac{K}{2r}$. This means that the stock must be above 0.4 in our fishery for there to exist a positive steady-state harvest rate. Further, if price is less than $P = \frac{c}{K}$ (= 0.25) fishing is not viable at any stock level $X \in [0, K]$. In comparison, we have established that harvesting in a stochastic setting can be optimal at stock levels well below 0.4 and finite prices (see Figure 4.2). Similarly, as stock increases it can be optimal for the fleet to stay active even though price is less than 0.25 and stock is 1. The reason is inertia; because of the uncertainty, it is better to keep the fleet active for a while in case things take a better turn, than paying the switching cost. The sensitivity of the switching curves with respect to price and stock volatility is presented in Figure 4.5. The degree of volatility does not affect the switching curves much. Note also how the deterministic steady-state curve matches the exit curve at high stock levels, and the entry curve at high price levels.

Figure 4.5: **Approximate Switching Curves. Base Case (thick lines), Deterministic (thick dash-dot line), High Volatility with $\sigma_X = 0.45$ and $\sigma_P = 0.30$ (thin dashed lines), and Low Volatility with $\sigma_X = 0.15$ and $\sigma_P = 0.10$ (thin lines).**



The growth rate of the stock limits the fishing fleet's harvest. The higher the intrinsic growth rate, the higher the maximum sustainable yield. Figure 4.6 shows approximate switching curves for alternative growth rates. The exit curve is fairly insensitive to changes in growth rate. The entry curve, on the other hand, changes with the growth rate - the higher the growth rate, the closer the entry curve is to the exit curve. This means that the fleet is active a larger share of the time when the growth rate is high, other things being equal. This is reasonable since a higher growth rate means a

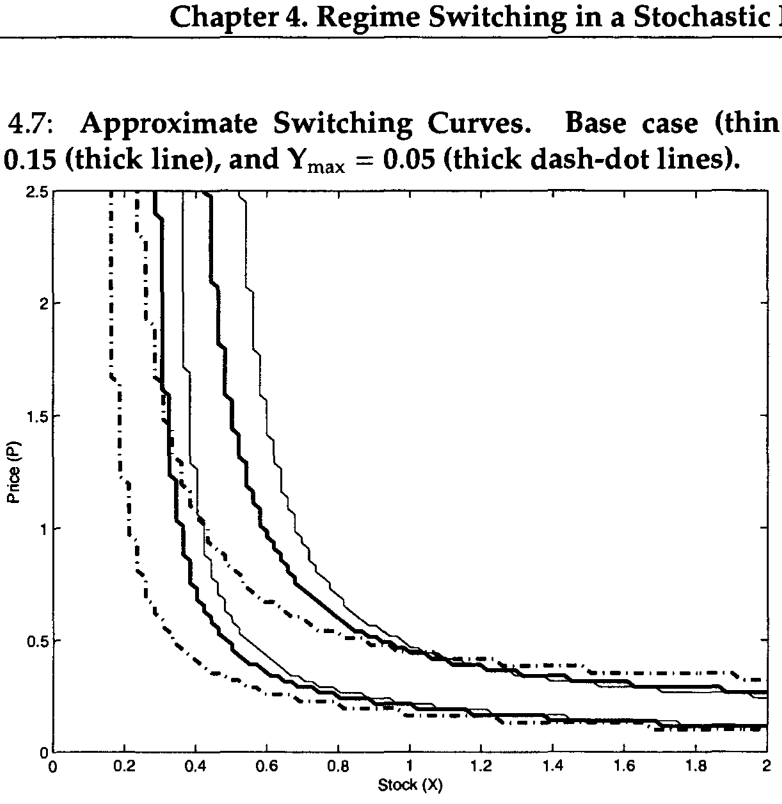
Figure 4.6: **Approximate Switching Curves. Base case r = 0.5 (thin lines), r = 0.25 (thick line), and r = 0.75 (thick dash-dot lines).**



larger stock growth and more fish available in the sea for harvesting. At high stock levels, the growth rate affects the switching curves very little.

So far we have assumed that we are dealing with a fishing fleet capable of harvesting at a rate twice as high as the maximum sustainable yield rate. In many fisheries, however, the capacity of the fishing fleet is not nearly as high as this and it is therefore interesting to see what happens to the fishery as we reduce the maximum harvest rate of the fleet. New switching curves are approximated for the fishery with maximum harvest rates 0.15 and 0.05, the latter being well below the maximum sustainable harvest rate. Other parameters are as presented in Table 4.1. As can be seen in Figure

Figure 4.7: **Approximate Switching Curves. Base case (thin lines), Y_{max} = 0.15 (thick line), and Y_{max} = 0.05 (thick dash-dot lines).**



4.7, a reduction in Y_{max} has little effect on the switching curves for high stock levels ($X > 0.9$). For lower levels of the stock, however, the change is significant and the smaller the maximum harvest rate, the closer the switching curves are to the price axis. The difference in sensitivity between high and low stock levels can be explained by the fact that the value of having a large stock is limited when the maximum harvest rate is small. This is similar to what Hannesson (1993) finds in his example of the capelin fishery. In addition, we see that the distance between the entry and exit curves seems to increase with Y_{max}. In a deterministic setting a maximum harvest rate of 0.05 would result in a constant harvest at full capacity for price $P \geq 0.60$. Simulations of the stochastic fishery (with $X_0 = 0.5$ and $P_0 = 1$) show that something similar happens there; the fleet will be active approximately 98% of the time when $Y_{\max} = 0.05$. This corresponds to an average stock of 0.71. Table 4.2 summarises the sensitivity statistics.

Table 4.2: **Fishery Characteristics by Maximum Harvest Rate, $\mathbf{Y_{max}}$**

	$Y_{\max} = 0.05$	$Y_{\max} = 0.15$	$Y_{\max} = 0.25$
Fishery open, share of time	98%	69%	45%
Biomass, mean	0.71	0.49	0.45
Biomass, standard deviation	0.28	0.19	0.12

The variation in stock level is seen to decrease with the maximum rate of harvest. The difference in long-run average biomass between the cases $Y_{\max} = 0.15$ and $Y_{\max} = 0.25$ is relatively small, which makes the fairly large difference in variation noteworthy. A larger maximum harvest rate enables the fleet to faster bring the stock back to its desired level when something changes. We are however dealing with a fleet that harvests either at $Y_{\max}$ or not at all, and a large $Y_{\max}$ could therefore cause increased volatility in biomass.

4.4 Summary and Conclusions

In this study we have seen how entry and exit curves can be computed when both the stock and the price of a natural resource evolve stochastically and when there are costs to changing the harvest rate. The production function, which was used to explain harvesting in the model, is linear in effort. Under the assumption of a constant cost per unit effort, we end up with a linear control problem. When maximising the total present value of net revenues over an infinite horizon, the optimal policy is consequently to harvest at full or at minimum capacity. The optimal policy has been defined by switching curves in stock-price space. By making the additional assumption that changing the harvest rate is subject to switching costs, we show that there exist two curves in stock-price space, one for activating the fleet and one for withdrawing the fleet from the fishery. These curves are numerically approximated and we study the fishery when employing the optimal switching policy. In a deterministic setting, the switch from harvesting at full or minimum capacity to maintaining an optimal stock level (steady state) occurs at most once with price constant. With stock and price uncertainty there is no steady state and it is optimal to switch back and forth between minimum and maximum harvest rates. The dual switching curves are a result of the combination of uncertainty and switching costs in the model.

Based on our initial choice of parameter values, we find that pulse fishing is the optimal behaviour of the fishing fleet and that it is optimal for the fishery to stay closed most of the time. Looking at the sensitivity of our results to parameter changes, price and stock volatilities do not affect the switching curves much. The maximum harvest rate of the fishing fleet, on the other hand, significantly affects the optimal switching curves.

Further, it turns out that one of the effects of having a larger harvesting capacity is a more stable stock, even under "bang-bang" harvest policy.

Many fisheries are being harvested by fleets, which also take part in other fisheries. From time to time, when the conditions allow for it, the fleet enters a particular fishery, harvests the stock down, before, once again, moving on to other fisheries. Such fisheries serve to illustrate the relevance of the regime-switching model defined and analysed in this paper. While we study a single fishery and assume lump-sum costs to increasing and decreasing the harvest rate, the resulting optimal behaviour, pulse fishing, is found in many real-world fisheries.

The current analysis can be extended in several ways. First, we assume a fixed capacity, which is reflected in the constant maximum harvest rate of the fishing fleet. The analysis can be extended by incorporating capacity as a third state variable (c.f. the deterministic model by Clark et al., 1979). When capital is subject to depreciation, the manager must decide upon an optimal investment policy in addition to the optimal harvest policy. This extension would however increase the complexity of the analysis dramatically. Second, the cost of changing the harvest rate can be assumed to increase with the magnitude of the adjustment made in fishing fleet or harvest rate. This will perhaps give a more accurate depiction of the reality in most fisheries. Another possibility for future research is to apply the model to a real-world fishery.

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Chapter 5

Cost Structure and Capacity in the Norwegian Pelagic Fisheries [1]

[1] A version of this chapter has been accepted for publication in Applied Economics.

Abstract

The parameters of the short-run cost function are estimated for three vessel types taking part in the Norwegian pelagic fisheries: purse seine vessels, trawlers, and coastal vessels. The generalised translog functional form is used. Estimates of returns to scale are calculated and the results indicate that there are substantial economies of scale in all vessel classes. We further investigate whether excess capacity varies with vessel size and age. The analysis suggests increased quotas per vessel to avoid rent dissipation. With the total allowable catch given, the number of participating vessels must be reduced.

5.1 Introduction

The broad opinion in the Norwegian fishing industry is that there is considerable excess capacity in the pelagic fisheries. Three vessel types participate in these fisheries; coastal vessels, trawlers, and purse seine vessels. However, in a study of the fisheries using data for 1994-96, Bjørndal & Gordon (2000) did not find evidence of large economies of scale. They conclude that most of the returns from scale effects have already been captured, and that only coastal vessels have more to gain by taking advantage of increasing returns to scale. The purpose of this study is to reconsider the capacity issue in the Norwegian pelagic fisheries using newly available data for the years 1998-2000. Multi-output cost functions are estimated and returns to scale (RTS) are computed for each of the three vessel classes as an indicator of capacity utilisation.

Despite the results of Bjørndal & Gordon (2000), we expect to find evidence of returns to scale in the fishery in question. Since the fishing fleet is constantly being renewed, returns to scale might change with vessel age. The continuous renewal of the fleet can also explain a possible change in returns to scale since Bjørndal and Gordon's study. If new vessels are larger than the ones they replace, overall returns to scale will be affected. We will therefore investigate if and how returns to scale vary with vessel age and size in each vessel class. This aspect has not been considered by Bjørndal & Gordon (2000) and might give further insight into the capacity issue. An understanding of how returns to scale vary between different segments of the fleet can be used to determine how best to allocate quotas among fleet segments, and to choose which vessels, if any, should be withdrawn from the fishery.

The pelagic fisheries are regulated with catch quotas and effort regulations. Total allowable catches (TACs) are set annually for commercial species and are then distributed as 'group quotas' among three classes of vessels. The further distribution of group quotas among vessels within a group differs depending on species and vessel class. The purse seine vessels are provided individual vessel quotas (IVQs) in all their fisheries. IVQs are allocated to trawlers in their main fisheries (primarily demersal species). For other species, trawlers are allowed to fish within maximum quotas. Under a maximum quota there is an upper limit to a vessel's total catch of a species. The sum of maximum quotas is larger than the group quota and the fishery is therefore closed before all vessels have landed their maximum quotas.[2] Maximum quotas are employed in all of the coastal vessels' fisheries.

A quota-transfer system called the unit quota system was introduced in the trawler and purse seine fleets in the early 2000 by the Norwegian government to address the capacity problem (Norwegian Ministry of Fisheries 2004). Under the unit quota system, the number of assigned (unit) quotas is larger than the number of participating vessels. If a vessel with

[2]See Aarland & Bjørndal (2002) on fisheries management in Norway.

unit quotas is withdrawn from the fishery, its quotas, reduced by 20% (redistributed among all remaining vessels in the fishery), can be transferred to and used by other vessels for 13 to 18 years.

Gordon (1954) identified how overcapitalisation and overfishing would be a problem in an open-access fishery. Under open access, fishing effort increases and the fish stock is depleted until fishing is no longer viable. Although the Norwegian pelagic fisheries are no longer open access, the regulatory regime has not eliminated the incentive to race for fish for every vessel in the fishery. Trawlers and coastal vessels still have to operate within maximum quotas in some or all of their fisheries. These vessels will have incentives to overcapitalise. Munro & Scott (1985) identify the problem of excess capacity in regulated fisheries, which they refer to as class II open access. Homans & Wilen (1997) illustrate how regulated open-access fisheries can have very high excess capacity. The introduction of individual transferable quotas (ITQs), an approach based on assigning property rights to the fish stocks, is a solution which has been proposed to address these problems (see e.g. Grafton, 1996).Individual vessel quotas are similar to ITQs but cannot be transferred between vessels. An IVQ system will all the same reduce the incentives to overcapitalise since every vessel is provided a guaranteed share of the TAC and therefore does not need to race for fish. Economies of scale can be a sign of excess capacity in a fishery.

The use of maximum quotas to regulate the coastal vessel's total harvest gives these vessels incentives to overcapitalise. We therefore expect to find evidence of increasing returns to scale in the coastal fleet. Trawlers largely operate under maximum quotas in the pelagic fisheries. These quotas are, however, mainly by-catch quotas to restrict by-catch in the trawlers' main fisheries, which primarily are demersal fisheries wherein trawlers are assigned IVQs. If the main fisheries determine the degree of capitalisation, there should be less overcapitalisation in the trawler fleet than in the coastal fleet. Overcapitalisation and scale economies might, however, still be present both in the trawl and the purse seine fisheries, as the introduction of IVQs in these fisheries happened quite recently. If there was excess capacity in the fisheries when the IVQ system was introduced, there might still be excess capacity if the vessels have not had strong enough incentives to reduce capacity. The IVQ system eliminates the incentive to race for fish. Vessel owners have, however, no incentive to withdraw vessels from the fishery, as they are not allowed to transfer or allocate the withdrawn vessels' quotas among other vessels. This changes if quotas are made transferable as under the individual transferable quota system or, to some degree, under the Norwegian unit quota system.

The rest of the paper is organised as follows. In the next section, the data set and the Norwegian pelagic fisheries are described. Section 5.3 presents the model and estimation results. The production structure of the fishery and policy implications are analysed in section 5.4. The final section summarises and concludes.

5.2 The Norwegian Pelagic Fisheries

The data for the empirical analysis have been made available by the Norwegian Directorate of Fisheries, which gathers data on a random sample of vessels annually. The data include information on expenditures, revenues, catches, and vessel specifications for vessels which are 13 metres overall length and above.

Three vessel types are defined in the data set: purse seine, trawl, and coastal vessels. The definitions are based on the technologies employed. Purse seine vessels use a purse seine net to catch schools of fish. After locating a school of fish, the vessel sails around it and surrounds the fish with a wall of net. By closing the bottom of the seine, a purse is formed. When the seine is pulled, the top of the purse is drawn closed and the fish are trapped in the net purse. The purse seine is very effective when it comes to harvesting pelagic schooling species like herring and mackerel.

Trawlers use a cone-shaped net (trawl) to harvest fish. By pulling the net through deep water (pelagic trawl) or across the bottom (bottom trawl), fish are scooped into the trawl. The trawlers operate mainly in the North Sea.

Vessels in the coastal fleet are not as homogenous as vessels in the two other vessel classes. Common factors for our observations on coastal vessels are an overall vessel length of 27 metres or less and a harvest of 50 tonnes or more of Norwegian spring-spawning herring. Apart from this, the coastal fleet constitutes a diverse group of fishing vessels including vessels employing the following fishing gear: gill net, hand line, long line, Danish seine, trawl, etc. Most coastal vessels operate close to the coast although this depends on among other things the fishing gear employed.

The data set covers the three-year period 1998-2000. Table 5.1 gives the number of observations per year. For each vessel, data are available on the following expenditures: fuel, product fees, bait etc., social costs, insurance (vessel and other), maintenance (vessel and gear), miscellaneous, labour, and depreciation based on historical cost. The catch and revenues data consist of quantity (kg) and value in Norwegian Kroner (NOK) of Norwegian spring-spawning herring, North Sea herring, mackerel, blue whiting, capelin, sandeel, and 'other species'. The following information is available on vessels: vessel type (purse seine, trawler or coastal vessel), length of vessel, gross registered tonnage, tonnage units, licensed capacity, and age. All fish species specified in the data set are pelagic with the

Table 5.1: **Observations per Vessel Type per Year**

	Purse seine	Trawler	Coastal vessel
1998	78	30	51
1999	65	25	55
2000	79	29	69
Total	222	84	175

exception of sandeel and 'other species'. Sandeel is a demersal species but it alternates between staying on or close to the bottom and swimming in schools in the water column. Blue whiting belongs to the cod family, but is nevertheless considered a pelagic species. Blue whiting is normally harvested at 300-400 meters depth. Norwegian spring-spawning herring, North Sea herring, and mackerel are schooling species most often found and harvested close to the surface. Capelin, a member of the salmon family, is also a pelagic species found in schools. While the other fish species mentioned here are caught along the Norwegian cost, in the North Sea, in the Norwegian Sea, and/or in the West-Atlantic, the capelin fishery takes place far north; from Spitzbergen in the west and eastward in the Barents Sea.

As can be seen in Table 5.1, the data set consists of 222 observations on purse seine vessels. In terms of revenues, Norwegian spring-spawning herring is most important to purse seine vessels, followed by mackerel, blue whiting, and North Sea herring (Table 5.2). Blue whiting is the largest species measured by volume. However, not all purse seine vessels harvest blue whiting, capelin, and sandeel. Data on trawlers are available for vessels that have caught more than 50 tonnes of Norwegian spring-spawning herring. The data set includes a total of 84 observations on trawlers (Table 5.1). As can be seen in Table 5.2, sandeel brings in the highest revenues for the average trawler followed by Norwegian spring-spawning herring, blue whiting, and mackerel. We have 175 observations on coastal vessels. All of these vessels have harvested more than 50 tonnes of Norwegian spring-spawning herring. The data set shows that coastal vessels do not participate in the blue whiting or sandeel fisheries (Table 5.2). The Norwegian spring-spawning herring fishery generates the largest share of revenues for the average coastal vessel and is also largest in terms of quantity. Landings of all pelagic species can be reduced to fish oil and

Table 5.2: **Average Harvest, Value, and Price per Vessel, 1998-2000, by Vessel Type (Harvest in Tonnes, Value in Thousand 2000 NOK, Price in Norwegian Kroner/kg)**

	Species	Quantity	Value	Price
Purse seine	Herring	4904	9244	1.885
	Mackerel	1198	6921	5.778
	Blue whiting	5638	3805	0.675
	Capelin	1746	1943	1.113
	Sandeel	304	229	0.753
	Other species	498	1038	2.083
	Total	14287	23179	1.622
Trawl	Herring	1138	1545	1.357
	Mackerel	55	243	4.437
	Blue whiting	1082	713	0.659
	Capelin	216	201	0.931
	Sandeel	3046	2272	0.746
	Other species	949	2275	2.396
	Total	6486	7249	1.118
Coastal vessel	Herring	1160	1669	1.439
	Mackerel	141	713	5.074
	Blue whiting	1	0	-
	Capelin	61	103	1.676
	Sandeel	0	0	-
	Other species	406	2602	6.404
	Total	1768	5087	2.877

fish meal. While landings of herring and mackerel are also delivered for human consumption, capelin and blue whiting are almost exclusively used in the production of fish meal and fish oil. A higher price is typically obtained for landings delivered for human consumption and, as a result, high quality herring and mackerel are normally delivered for human consumption. Both harvesting method and the way fish are stored vary between the fleets, affecting the quality and consequently the price of landed fish.

Average first-hand prices of harvest, measured in 2000 NOK, by fleet and species are presented in Table 5.2. The table confirms that prices depend on vessel type. Purse seine vessels obtain the highest price for almost every species. The exception is capelin for which coastal vessels obtain the highest price. Trawlers obtain the lowest prices for all species. Note that average price of 'other species' is not comparable between vessel classes. For coastal vessels, other species are seen to be very valuable. As some of these vessels utilise fishing gear which makes it possible to harvest and land valuable fish of very high quality, the high price obtained for these catches raises the average price of 'other species'.

The vessels range in age from less than one year to 62 (purse seine), 51 (trawlers), and 111 years (coastal vessels). The average vessel in the data set is 23 years old. The trawlers are on average the oldest fleet segment, followed by purse seine and coastal vessels. Table 5.3 shows upper limits for capacity and age quartiles by vessel group. Tonnage units, a measure of vessel size, are used as measure of vessel capital for purse seine vessels and trawlers, whereas gross registered tonnage (GRT) are used as the capital measure for coastal vessels. The available data do not allow us to use the same capital measure for all three vessel types. For the vast majority of coastal vessels, data are available on GRT and not on tonnage units, for most trawlers and purse seine vessels, on the other hand, only data on tonnage units are available.

Table 5.3: **Upper Limits for Capacity and Age Quartiles (Capacity in Tonnage Units, T, or Gross Registered Tonnage, GRT, Age in Years)**

	Capacity			Age		
	Purse S. (T)	Trawl (T)	Coastal (GRT)	Purse S.	Trawl	Coastal
Q1	654	265	54	11	19	11
Q2	983	308	93	21	24	16
Q3	1567	402	133	33	36	30

5.3 Empirical Specification and Estimation

The duality approach offers a framework for analysing the harvest technology and cost structure of the fishing firms. Empirical knowledge of the relationship between input factors and outputs can be used to analyse capacity utilisation in the fishery. The purpose of this section is to gain the necessary empirical knowledge of harvesting for the three vessel types in the Norwegian pelagic fisheries. We start out by specifying the empirical model.

5.3.1 Empirical Model

The quantity landed by a vessel is given by the vessels' quotas if the quota constraints are binding.[3] The rational fishermen then minimise costs given their quota restrictions, rather than maximise profits.[4] Harvest can in this case be explained by a harvest or production function $Y = f(X, K)$, where Y is an output vector, K is capacity or capital (assumed fixed), and X is an input vector. The fishermen's cost minimisation problem can thus be written as:

$$VC(W, Y, K) = \min_{X \geq 0} \{W \cdot X : f(X, K) = Y\}, \qquad (5.1)$$

where W is a vector of input prices (variable inputs).

The vessels' variable costs are mainly wages, fuel, and vessel and gear maintenance. As crew remuneration is a given fraction of the vessel's catch value, we disregard wages. The data are therefore used to define two price indices. First, a price index for fuel w_f that measures the cost of purchasing fuel. The data set does not include information on the quantity of fuel used or purchased. A proxy variable for fuel quantity is calculated based on a Cobb-Douglas aggregator function. Equal weight is given to vessel length and total catch quantity in the aggregator function and the price index of fuel is defined as expenditure on fuel divided by the proxy variable. Second, we define the vessel-price index w_v as expenditure on

[3]We assume that vessels for which the quota constraints are not binding also minimise costs.

[4]It follows that we assume price taking behaviour.

insurance (vessel and other), maintenance (vessel and gear), bait etc., and 'other costs' divided by the vessel's total catch quantity. The vessel-price index is an aggregate index measuring the cost of maintenance of vessel and gear and the insurance cost.

Summary statistics for price indices can be found in Table 5.4. While the fuel price index has been increasing significantly over the period, the vessel price index is seen to be more stable. The increase in the fuel-price index is likely to reflect the corresponding increase in the price of oil. The coastal vessels have the lowest price index of fuel and the highest price of maintaining vessel and gear. The difference in fuel prices between purse seine vessels and trawlers is seen to be small whereas the vessel price index is higher for purse seine vessels than for trawlers.

The generalised translog functional form (Caves et al., 1980) is used to specify the cost function:

$$\begin{aligned} lnVC_t = \alpha &+ \sum\nolimits_i \alpha_i \ln w_i + \frac{1}{2}\sum\nolimits_i \sum\nolimits_j \beta_{ij} \ln w_i \ln w_j \\ &+ \sum\nolimits_m \alpha_m y_m^{(\lambda)} + \frac{1}{2}\sum\nolimits_m \sum\nolimits_n \beta_{mn} y_m^{(\lambda)} y_n^{(\lambda)} \\ &+ \sum\nolimits_i \sum\nolimits_m \beta_{im} \ln w_i y_m^{(\lambda)} + \alpha_K \ln K + \frac{1}{2}\beta_{KK} (\ln K)^2 \\ &+ \sum\nolimits_i \beta_{iK} \ln w_i \ln K + \sum\nolimits_m \beta_{mK} y_m^{(\lambda)} \ln K + \alpha_t D_t + e_t, \end{aligned} \tag{5.2}$$

where VC is the sum of variable costs in period t, D_t is a year dummy,[5] e is

[5]As an alternative to additively including dummy variables for year like we have done here, terms in the cost equation could have been multiplied by the dummy variables, giving us the opportunity to analyse if and how different parameters change from year

an error term, i, j are input factors (fuel and vessel, as defined above) and m, n are outputs. The superscript in parentheses represents the Box-Cox transformation of outputs: $y^{(\lambda)} \equiv (y^{\lambda} - 1)/\lambda$, where λ is a transformation parameter. $y^{(\lambda)} \rightarrow \ln y$ as $\lambda \rightarrow 0$, thus with $\lambda = 0$ the model reduces to the standard translog function. As we are dealing with multi-product

Table 5.4: **Factor Price Indices by Vessel Type, 1998-2000 (Standard Errors in Parentheses)**

		w_f	w_v
Purse seine	1998	51.36 (13.68)	26,179.55 (12,914.62)
	1999	61.66 (17.72)	23,201.57 (12,069.91)
	2000	96.96 (31.05)	24,040.51 (11,055.89)
Trawl	1998	49.06 (22.72)	8,490.27 (4,562.29)
	1999	62.83 (20.59)	6,960.80 (3,226.28)
	2000	108.90 (41.30)	6,882.66 (2,707.91)
Coastal vessel	1998	33.79 (15.37)	5,454.68 (3,051.37)
	1999	38.38 (16.74)	5,235.02 (2,361.58)
	2000	57.87 (21.61)	5,528.79 (2,646.39)

firms for which zero-output observations may occur, it is inappropriate to use the ordinary translog functional form. The generalised translog function allows for zero-output observations and is therefore preferred. Several other functional forms have been suggested for estimating cost functions for multi-product firms, including the composite cost function of Pulley & Braunstein (1992). Pulley and Braunstein found that when the generalised translog function is a close approximation to the standard

to year.

translog function, i.e., for small values of λ, the generalised translog might cause problems when estimating economies of scope. The generalised translog functional form is used in the current analysis despite the reported shortcomings.

By applying Shephard's Lemma, the cost share equations associated with equation 5.3 can be written as:

$$s_i = \frac{\partial \ln VC_t}{\partial \ln w_i} = \alpha_i + \sum\nolimits_j \beta_{ij} \ln w_j + \sum\nolimits_m \beta_{im} \ln y_m^{(\lambda)} + \beta_{iK} \ln K + u_i, \qquad (5.3)$$

where s_i is a cost share, and u_i is an error term. Equation 5.3 and the share equation for fuel (s_f) are estimated using iterative Seemingly Unrelated Regression (SUR). By dropping one of the share equations from the system, the singularity problem, arising from the fact that the cost shares sum to one, is avoided. The iterative procedure converges to the maximum-likelihood results. Maximum-likelihood estimates of the cost function and share equations are invariant to which equation is dropped (Barten, 1969). The following estimation routine is used: The system of equations is estimated for different values of the Box-Cox transformation parameter, $0 < \lambda < 1$. Estimation results and $\hat{\lambda}$ are reported for the regression that yields the highest log-likelihood value.[6]

For the cost function to be well behaved, it must satisfy homogeneity of

[6]As a consequence of the estimation procedure, $\hat{\lambda}$ is taken as given when the other parameters of the cost function are estimated. The reported standard errors are therefore lower than they would be if all parameters, including the Box-Cox transformation parameter, $\hat{\lambda}$, were estimated simultaneously.

degree one, monotonicity, and convexity in factor prices (Diewert, 1974). Linear homogeneity can be imposed by adding the following linear parametric restrictions on the estimated cost function: $\sum_i \beta_i = 1$, for $i = f, v$, and $\sum_{if} \beta_{if} = \sum_{iv} \beta_{iv} = \sum_{iK} \beta_{iK} = \sum_{im} \beta_{im} = 0$, for $i = f, v$, which must hold for all m (outputs). Monotonicity and convexity in prices can be tested after estimation and are satisfied if the fitted cost shares are positive and the Hessian matrix of the cost function with respect to factor prices is negative semi-definite.

5.3.2 Measuring Capacity and Capacity Utilisation

There is excess capacity in a fishery if the potential catch of the current fleet is larger than the current catch. Excess capacity is a short-run measure as it is self correcting in a well-functioning market. Excess capacity should not be confused with overcapacity, which is a long-run concept measuring potential output against a target level of output (see e.g. Ward et al., 2004). To measure capacity utilisation we need to define capacity output. How much is produced at full capacity? The economic literature does not provide an unambiguous definition and several different approaches have been suggested.

There is a large literature on capacity and capacity utilisation. The focus will in this paper be on economic definitions as opposed to physical definitions. In the following we will briefly present some measures of capacity suggested in the economic literature. For a more comprehensive presentation of different capacity measures, see e.g. Coelli et al. (2002). Klein (1960) suggested a measure of capacity defined by the tangency point between the short run (SRAC) and long run average cost (LRAC) functions. Berndt & Morrison (1981) defined capacity output as the minimum point on the SRAC function. Coelli et al. (2002) suggest a capacity measure where output capacity is given by the point that maximises short-run profits. Segerson & Squires (1990) show how single-output measures of capacity can be generalised to the multi-output case.

Estimates of returns to scale can be used as indicators of capacity utilisation. If we define capacity output as the output that minimises short run average costs cf. Segerson & Squires (1990), increasing returns to scale implies excess capacity, as minimum average cost corresponds to RTS=1. An indicator of returns to scale for a multi-product firm with a fixed factor corresponding to the cost function (5.3) is given by:

$$RTS = \left(1 - \frac{\partial \ln VC}{\partial \ln K}\right)\left(\sum_n \frac{\partial \ln VC}{\left[\partial y_n^{(\lambda)}\right]} y_n^\lambda\right)^{-1} \tag{5.4}$$

where RTS greater (less) than one means increasing (decreasing) returns to scale (cf. Caves et al., 1980; Panzar & Willig, 1977).

Capacity utilisation in the Norwegian pelagic fisheries is analysed in section 5.4 but first we need to estimate the model.

5.3.3 Estimation Results

We now turn to the estimation of cost functions for the pelagic fisheries. There has been no significant change in the technology employed in these fisheries over the three-year period in question. There has, on the other hand, been a slight change in the size of the fish stocks. To find out if this has any effect on the estimated cost parameters, tests using dummy variables for year were carried out (cf. equation 5.3). The results did not show any significant change in costs. The annual data are therefore pooled. All right-hand side variables are centred on the mean of the variable in the data set for estimation.

Different vessel types take part in different fisheries. This is reflected in the output definitions of the estimated cost functions; the same outputs are not defined for the three vessel types, as can be seen in Table 5.5. Aggregation of different species is done based on quantity. Outputs consisting of more than one species are therefore measured in total quantity. Based on prior knowledge of the fisheries, cost functions were estimated for each vessel type with alternative output definitions. The output definitions that scored highest on number of significant variables, adjusted R-squared, etc. when estimating the cost functions were chosen. Notice how the defined outputs reflect similarities among species in terms of behaviour as well as other factors like distance from shore to fishing areas, if the species for the most part are delivered for human consumption or for reduction, etc. Estimation results are shown in Table 5.6. For all vessel classes, the

Table 5.5: **Output Definitions**

	Output A	Output B	Output C	Output Others
Purse seine	Herring	Mackerel Capelin	Blue whiting Sandeel	Other species
Trawl	Herring Mackerel Capelin	Sandeel	-	Blue whiting Other species
Coastal vessel	Herring	-	-	Blue whiting Capelin Mackerel Sandeel Other species

estimated cost functions explain approximately 95% of the variation in the underlying data. Tests of regularity conditions were carried out and the results imply that monotonicity and convexity in prices are satisfied. Most of the estimated parameters are significant at the 5% level. The fit of the models are therefore reasonable.

Having established and estimated the model, we now turn to the analysis of production structure and implications for regulation of the fishery.

5.4 Production Structure and Policy Implications

Before we can say anything about policy implications we need to characterise the structure of the production processes. The main purpose is to analyse returns to scale in different vessel classes to establish if excess ca-

Table 5.6: **Generalised Translog Cost Function, Estimates with Standard Errors: Purse Seine, Trawl, and Coastal Vessel**

	Purse seine		Trawl		Coastal vessel	
Parameter	Estimate	Std.Err.	Estimate	Std.Err.	Estimate	Std.Err.
λ	0.589		0.651		0.0720	
α_f	0.240**	0.002	0.340**	0.003	0.183**	0.003
α_v	0.760**	0.002	0.660**	0.003	0.817**	0.003
α_{ff}	0.171**	0.002	0.199**	0.004	0.130**	0.003
α_{vv}	0.171**	0.002	0.199**	0.004	0.130**	0.003
α_{fv}	-0.171**	0.002	-0.199**	0.004	-0.130**	0.003
α_A	0.157**	0.052	0.136**	0.044	0.063	0.039
α_B	0.056**	0.016	0.063**	0.013		
α_C	0.083**	0.008				
α_{ot}	0.025**	0.006	0.065**	0.016	0.034	0.025
β_{AA}	-0.418*	0.240	-0.118	0.083	0.196**	0.059
β_{BB}	0.098**	0.034	-0.012	0.014		
β_{CC}	0.019*	0.011				
β_{otot}	0.007	0.007	-0.015	0.021	0.165**	0.052
β_{AB}	-0.036	0.058	0.005	0.039		
β_{AC}	-0.007	0.030				
β_{Aot}	0.015	0.024	-0.027	0.032	-0.131**	0.045
β_{BC}	-0.002	0.010				
β_{Bot}	-0.001	0.009	-0.046**	0.013		
β_{Cot}	-0.005	0.003				
β_{fA}	0.039**	0.012	0.007	0.012	0.059**	0.006
β_{vA}	-0.039**	0.012	-0.007	0.012	-0.059**	0.006
β_{fB}	0.014**	0.004	0.047**	0.005		
β_{vB}	-0.014**	0.004	-0.047**	0.005		
β_{fC}	0.023**	0.001				
β_{vC}	-0.023**	0.001				
β_{fot}	-0.006**	0.001	0.032**	0.005	0.025**	0.005
β_{vot}	0.006**	0.001	-0.032**	0.005	-0.025**	0.005
α_K	-0.047*	0.028	-0.069	0.059	0.018	0.039
β_{KK}	0.022	0.079	0.461*	0.265	-0.096	0.091
β_{fK}	0.040**	0.006	0.087**	0.019	0.024	0.025
β_{vK}	-0.040**	0.006	-0.087**	0.019	0.008	0.034
β_{AK}	0.035	0.124	-0.046	0.104	0.019	0.058
β_{BK}	-0.060	0.039	-0.092	0.057		
β_{CK}	-0.021	0.018				
β_{otK}	-0.010	0.012	-0.067	0.066	-0.039	0.060
α_0	16.014**	0.012	15.049**	0.013	14.297**	0.015

pacity is present and, if so, to what extent. We start by looking at measures of elasticity. Table 5.7 shows returns to scale (equation 5.4) and input-price

Table 5.7: **Returns to Scale and Input Price Elasticities with Standard Errors: Purse Seine, Trawl, and Coastal Vessel**

		Coefficient	Standard Error
Purse seine	RTS	3.252	0.494
	Fuel	-0.046	0.012
	Vessel	-0.014	0.004
Trawl	RTS	4.037	0.640
	Fuel	-0.076	0.013
	Vessel	-0.039	0.007
Coastal vessel	RTS	10.140	4.727
	Fuel	-0.110	0.015
	Vessel	-0.025	0.004

elasticities calculated for each vessel type and evaluated at mean levels. The reported own-price elasticities are all significant at a 5% level, negative, and indicate that the response to price changes is rather inelastic. Purse seine vessels seem to have a more inelastic response to changes in both of the two input prices than the other vessel types. Bjørndal & Gordon (2000), who used the same price indices in their analysis, also report inelastic factor demand. In his study of the ITQ regulated surf clam and ocean quahog fishery, Weninger (1998) reports inelastic input-price responses. Dupont (1991) estimates a normalised quadratic restricted profit function for the British Columbia salmon fishery, which is regulated by input restrictions. Her empirical analysis shows that the elasticities of the unrestricted inputs are inelastic. Other studies in the fisheries economics literature report elastic factor demand. Most of the fisheries analysed in these studies are, however, subject to other regulatory regimes.

We now turn to the question of whether there is excess capacity in the Norwegian pelagic fleet. The estimates of returns to scale reported in Table 5.7 are significant at a 5% level, and they indicate substantial economies of scale in every vessel class. Recall that we used measures of vessel size as a proxy for capital: tonnage units measure capital for purse seine vessels and trawlers, and GRT measures the capital for coastal vessels. For purse seine vessels and trawlers, the estimates are significantly larger than two at the 5% level. This strongly implies that there is considerable excess capacity in these fisheries. Estimated RTS are very high for coastal vessels, but the standard error for this estimate is large and we cannot establish whether RTS are above one for coastal vessels at the 5% significance level. Bjørndal & Gordon (2000) found evidence of returns to scale in their analysis of the fishery. Their estimates of RTS are, however, much smaller than the ones reported in Table 5.7.

The difference in estimated returns to scale between Bjørndal & Gordon (2000) and this study can be due to changes in vessel quotas. If vessel quotas were much higher in the period for which Bjørndal and Gordon did their study, this can explain why the degree of returns to scale has increased in the meantime. The capelin fishery was closed from 1994 through 1998, a period that covers the entire data set used by Bjørndal and Gordon (the years 1994-96). Capelin is, on the other hand, an important source of income for some of the vessels in our data set. The quotas of Norwegian spring-spawning herring have also increased, while quotas of North Sea herring and mackerel, with the exception of the coastal fleet's mackerel quota, have been reduced. The total quotas of herring, the commercially most important pelagic species, have however increased rather than decreased. The difference in quotas per vessel does therefore not seem to explain the relatively large difference in estimated returns to scale between the study by Bjørndal & Gordon (2000) and our study. As we are dealing with pelagic fisheries for which the stock-output elasticity is expected to be small (cf. Bjørndal, 1987), changes in stock should not affect estimated cost parameters very much.

Several other studies in the fisheries economics literature deal with the question of returns to scale. Asche et al. (2002) find evidence of substantial scale economies for Norwegian cod trawlers operating under an IVQ system. Increasing RTS are also reported in other studies of fisheries, e.g. by Weninger (1998) in his analysis of the surf clam and ocean quahog fishery. As Asche et al. (2002) note, most of the RTS estimates in the fisheries economics literature show decreasing returns to scale (e.g. Alam et al., 2002; Squires, 1987a,b; Squires & Kirkley, 1991). The regulatory regime in fisheries where one finds decreasing RTS is typically different from that of the fisheries with increasing RTS.

The fact that regulations have been changing over the years might suggest that returns to scale vary with vessel age. This could be the case if the current regulatory regime is taken into account when investments in vessels are made. It seems most likely to find evidence of such change in the purse seine fleet, where an IVQ system was introduced in the late 1980s. If vessels built after the introduction of the IVQ system have lower RTS than other purse seine vessels, this could indicate that the introduction of IVQs in the purse seine fleet has helped reduce excess capacity and consequently reduced rent dissipation in the fishery. The problem of excess capacity will then become smaller as time passes by. It might also be useful to investigate whether returns to scale change with vessel capacity within vessel classes. Such variations would have implications for how quotas should be reallocated to take advantage of scale effects. Fishing vessels are provided quotas depending on, *inter alia*, the size of the vessel and size could therefore matter. It has also been suggested that the smaller vessels have been provided relatively large shares of the TAC (Aarland & Bjørndal, 2002). If this is true, we should find lower returns to scale for smaller vessels.

To find out whether returns to scale vary with vessel capacity or vessel age, RTS are calculated for the average vessel in every capacity and age quartile. Capacity and age ranges for the quartiles can be found in Table 5.3. Results with standard errors are reported in Tables 5.8 and 5.9. Table 5.8 shows returns to scale for the average vessel by vessel-age quartile. The results do not show significant differences between age quartiles in any vessel class at the 5% significance level. We nevertheless find that the point estimate of RTS for purse seine vessels is increasing with vessels' age. The point estimate of RTS for the youngest purse seine vessels ($\leq$ 10.75 years of age) are 2.97, while the same estimate for the oldest vessels are 3.63. For trawlers the point estimates of RTS are seen to be lowest for the two age quartiles in the middle. The four point estimates for coastal vessels are almost identical, but only for quartiles Q1 and Q3 are RTS significantly larger than unity. Returns to scale for the average vessel by vessel-capacity

Table 5.8: **RTS by Vessel Age with Standard Errors. RTS for Average Vessel in Quartile Reported.**

	Purse seine	Trawl	Coastal vessel
Q1	2.969 (0.461)	4.470 (0.939)	10.395 (4.501)
Q2	3.274 (0.604)	3.757 (0.508)	9.858 (4.745)
Q3	3.423 (0.520)	3.719 (0.528)	9.232 (3.943)
Q4	3.628 (0.568)	4.511 (0.862)	11.493 (7.054)

Table 5.9: **RTS by Vessel Capacity with Standard Errors. RTS for Average Vessel in Quartile Reported.**

	Purse seine	Trawl	Coastal vessel
Q1	3.095 (0.483)	3.206 (0.325)	13.628 (9.908)
Q2	3.594 (0.572)	3.795 (0.544)	11.881 (6.106)
Q3	3.419 (0.587)	4.986 (1.206)	11.191 (5.573)
Q4	3.245 (0.699)	18.657 (26.540)	10.313 (4.827)

quartile are reported in Table 5.8. Looking only at the point estimates, the results suggest that RTS in the trawler fleet are increasing with capacity, and the largest trawlers seem to have very high returns to scale. In the coastal fleet, all the vessels seem to have very high scale returns. The standard errors of the estimates are however very large, and RTS are not significantly larger than one for any of the vessel-capacity quartiles. There is little or no difference in the point estimates of RTS among purse seine vessels of different sizes. At the 5% significant level we cannot state that there are significant differences in RTS between vessels of different size (capacity) in any vessel class. This study therefore does not find statistical support for the hypothesis that the degree of excess capacity in the fishery depends on vessel size.

The fact that we did not find significant differences between age and capacity quartiles for any vessel class suggests that the problem of excess capacity is present in a large part of the pelagic fleet. As seen in Tables 5.8 and 5.9, nearly all estimates of the RTS indicator for the purse seine and trawler fleets are significantly larger than two. The exceptions are the two estimates for capacity quartiles Q4. For trawlers, the standard error of this estimate is very large, whereas we only have statistical support to say that RTS are significantly larger than 1.87 not 2.00 for capacity quartile Q4 of the purse seine fleet. The significance of RTS estimates for the coastal vessels, as presented in Tables 5.8 and 5.9, are not nearly as high.

As we noted in section 5.3.2, full capacity can be defined as the output quantity that minimises average costs, i.e., the output level for which RTS=1. When the vessels are producing several outputs, there is more than one way to capture the scale benefits as many different output combinations result in RTS=1. By looking at ray measures of economic capacity, where it is assumed that all outputs increase or decrease in fixed proportions, the problem can be reduced to a single-product problem and subsequently solved for RTS=1. Ray returns to scale equal unity corresponds to the minimum point on the ray average cost curve. When trying to apply this to the estimated cost functions for the Norwegian pelagic fishery in order to calculate the degree of excess capacity, we find that the average-cost curves do not have a minimum for any of the vessel groups (i.e., ray returns to scale are never equal to one). The estimated average cost curves are decreasing everywhere for increasing (ray) output and do not have the "U" shape we generally expect. Remember that the translog functional form provides a good approximation to the underlying function in the point of approximation. As we move away from this point, however, the translog function performs poorer and poorer. A very plausible explanation for why the estimated ray-average cost curves do not have the "U" shape is that our observations are far from full capacity utilisation. Although this means we cannot calculate the degree of excess capacity, it is another strong indication of high excess capacity in the Norwegian pelagic fishery. Even if the ray average cost curves would have had the expected "U" shape, an estimate of capacity utilisation would have been highly uncertain since the observations in the data set only cover the part of the cost curve where there is a high degree of excess capacity.

Making the standard assumption that a manager wants to maximise net revenues from the fishery, estimates of cost functions can be used to suggest how quotas should be optimally redistributed both within and between vessel classes. Our data set only contains information on vessels participating in the pelagic fisheries. This means that we have data on all purse seine vessels but only on distinct groups of vessels from the coastal and trawler fleets. The full production structure of the fleets should be taken into account when analysing the optimal reallocation of quotas between vessel classes. This question will therefore not be addressed in the current analysis.

5.5 Concluding Remarks

We set out to estimate cost functions for the different vessel groups taking part in the Norwegian pelagic fisheries. The purpose was to measure scale economies in the fishing fleet. Cost functions were estimated for coastal vessels, trawlers, and purse seine vessels using annual data covering the period 1998-2000. In a similar analysis, but using data for the years 1994-96, Bjørndal & Gordon (2000) estimated returns to scale to be increasing but close to one. According to their results, only slight reductions in average cost can be gained by taking advantage of scale effects in the fishery. Despite the findings by Bjørndal & Gordon (2000), the common opinion in the industry has been that there is substantial excess capacity in the pelagic fishery. This discrepancy and the availability of new data motivated the current analysis.

We find evidence of substantial returns to scale in the Norwegian pelagic fisheries. Our estimates of returns to scale in the trawl and purse seine fleets seem robust and suggest that large scale economies are present. Estimated returns to scale for coastal vessels are also substantial but the estimates are not significantly different from one. It should be noted that the measure of returns to scale used in the analysis is only an indicator of the actual scale economies of the fishing fleet. Nevertheless, the results give support to the industry opinion of large excess capacity in the pelagic fleet. The results are also in accordance with the economic literature on regulated open-access fisheries.

We have looked at several explanations for why we find large returns to scale in the Norwegian pelagic fishery, while Bjørndal & Gordon (2000) only found evidence of minor returns to scale. First, a decrease in quotas was suggested as a possible explanation. However, when looking at data on annual quotas we could not find support for this hypothesis; quota differences alone would not be enough to explain the difference in returns to scale. Second, the fleet is constantly being renewed and the fleet studied by Bjørndal and Gordon is not the same as the fleet in our data set. To see if this could explain the difference in RTS we tested if the degree of returns to scale varies with vessel age. We did not find strong evidence for this either.

Excess capacity seems to be present in all vessel classes, and we find the degree of excess capacity within each vessel class to be independent of vessel age and size. This suggests that quotas per vessel should be increased in every segment of the fleet. From an economic perspective, excess capacity should be dealt with by withdrawing the least effective vessel from the fishery until there no longer is any excess capacity. Subsequently, catch quotas should be reallocated both within and between vessel classes to take advantage of scale effects. The largest gain (measured in cost reductions) is obviously realised by reallocating quotas to the vessels with the highest returns to scale. Our analysis does not point towards an unambiguous solution to the problem of how best to reduce fishing capacity and reallocate quotas. To better answer these questions, further analysis of the cost and harvest structure of the Norwegian fishing fleet is required.

Until recently, there have been few incentives to reduce capacity in the pelagic fleet. The recent introduction of a unit quota system in the purse seine and trawl fisheries has changed this. The analysis suggests that quotas per vessel should be increased considerably to take advantage of scale effects. As the total allowable catch in the fishery is given, increased vessel quotas can only be realised by withdrawing vessels from the fishery. The unit quota system has the potential of making such capacity reduction achievable. It will be interesting to see if the incentives provided by the unit quota system are strong enough to reduce the excess capacity in the fishery.

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