Some economic aspects of relevance for harvest rules for marine fish stocks

A perspective from the Northeast Atlantic

by

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Preface

How can economists contribute in the process of developing harvest rules for marine fish stocks? Having worked for several years in the fishery management of Norway, where harvest rules are based on biological advice exclusively, I witnessed this issue to become progressively more important. When, in 2002, the Institute of Marine Research in Norway announced a position as a research fellow to do empirical economic research, of relevance for developing harvest rules for some of the marine fish stocks in our area, I applied for the job.

The answer to the question is obvious within the discipline of bioeconomics, where optimal exploitation of fish stocks is a core field. How come then, that this knowledge is not more widely applied when developing operating harvest rules for fish stocks in the Northeast Atlantic? One reason may be that managers have focused more on harvest rules that keep fish stocks within safe biological limits than on harvest rules that aim towards optimal exploitation. Another reason may be that most fish stocks in the Northeast Atlantic are shared stocks. Decisions on harvest rules for such stocks require cooperative management, and the managers may have found it easier to base such decisions on biological than on bioeconomic advice (since the latter may differ between parties). Finally, the long-term existence of the International Council for the Exploration of the Sea (ICES) has also facilitated harvest rules to be based on biological advice.

However, during the last decade there has been a growing awareness within management agencies and the ICES that there should be a shift in focus in the management of marine fish stocks. Without compromising the need to keep fish stocks within safe biological limits, there has been an increased focus on optimal exploitation. As a consequence, there is an increasingly recognition of the need to apply bioeconomics to develop optimal harvest rules.

This dissertation focuses on some empirical economic aspects of relevance for harvest rules for marine fish stocks in the Northeast Atlantic. The dissertation consists of three essays as well as an introduction and a concluding section. The first essay focuses on how costs in two major Norwegian fisheries depend on output and the fish stock utilised. The second essay evaluates the consequences of alternative harvest rules for a specific fish stock. The third essay discusses game-theoretic aspects of relevance for a fish stock that becomes straddling at high stock levels.

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Content

Introduction

1. Introduction

Economically efficient management of fish stocks requires consideration of optimal utilisation. Such utilisation is often known as a harvest rule, or investment strategy, for the stock. A sole owner of a fish stock, who controls the physical capital needed to harvest its yield, can solve this management problem by using appropriate models, of which Gordon (1954), Schaefer (1957) and Clark and Munro (1975) have illuminated the basic structures.

However, for commercial marine fish stocks in the Northeast Atlantic, sole ownership is more the exception than the rule. First, the majority of these are shared fish stocks that are managed cooperatively between two or more different states. Second, while the state may limit participants and total harvest in the fishery, it is the industry, rather than the state, which controls the physical capital needed to harvest the resource.

The dichotomy between management authorities and industry as decision-makers is quite natural, and reflects a division of expertise between the state and the industry. With shared fish stocks, there is a need for internationally agreed harvest rules (investment policies) for the fish stocks. This is a task for the management agency of the relevant parties utilising the resource. Even if a fish stock were confined within the Exclusive Economic Zone (EEZ) of one party, the existence of various national user groups would necessitate that national administration had the final word concerning harvest rule. Being aware that a fishery often targets several age groups of a fish stock, the state also has a responsibility to ensure an optimal exploitation pattern in the fishery. This responsibility implies management measures such as mesh size regulations and closed areas (or seasons) in order to prevent the catch of juvenile fish, thus enhancing the growth potential of the stock[1].

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[1]   When two or more fleets that exploit the same fish stock, differ concerning exploitation pattern, the allocation of a national quota on fleets also affect the overall exploitation pattern in the fishery. Optimisation of the overall exploitation pattern thus implies optimal sharing keys and game theoretic aspects to obtain such keys. For applications to the Northeast Arctic cod stock, see Sumaila (1997) and Armstrong (1999).

On the other hand, the industry can be expected to have far better knowledge than the management agency concerning optimal investment in the physical capital necessary to harvest the resource. Nevertheless, the management agency does have a responsibility to stimulate industry's incentives to avoid overinvesting in physical capital. This can be done by establishing individual vessel quotas (IVQ) in the fishery and/or making these transferable (ITQ). Hannesson (2000) has shown that even though ITQs provide better incentives for correct investment than an open-access fishery, optimal investment will also depend on the remuneration system for the crew (since this may imply wages that deviate from the opportunity cost of labour).

This separation of investment decisions related to the fish stock (the harvest rule) and investment decisions related to the physical capital between national administration and the industry makes it important to investigate the interrelationship between investment policies for a fish stock on the one hand and investment decisions in physical capital as well as variable costs in the fishery on the other hand. A stock investment programme characterised by large fluctuations in yield may have other consequences for investment in physical capital than a programme where year-to-year fluctuations in yield are reduced. Moreover, a stock investment programme that implies a large biomass may have other consequences for harvesting costs than investment programmes that target low biomass. Finally, if the stock is straddling or shared with another nation, it is important to acknowledge the economics of exploitation of the other party, as well as the payoff from cooperation / non-cooperation.

Consideration of how investment decisions related to a fish stock may depend on expected economic behaviour by the industry, as well as on incentives to cooperate when managing shared stocks, are fundamental in this dissertation. The dissertation consists of three empirical essays. The first of these discusses how variable unit costs in two output-regulated fisheries depend on output and stock, the knowledge of which is important when establishing harvest rules for such stocks. The second essay discusses whether a harvest rule characterised by target fishing mortality is superior to a rule characterised by target escapement when price falls in output. The third essay deals with game-theoretic aspects of relevance for the management of a straddling fish stock.

The fishery model(s) developed by Gordon (1954), Schaefer (1957) and Clark and Munro (1975) provides good general and theoretical insights to the problems discussed in the essays. There is, however, a need to fill these model(s) with empirical content, and the three essays of this dissertation aim to do that. To appreciate the link between the empirical model in each essay and the theoretical fishery model, the theoretical foundation for each essay will be discussed before the essays are presented. In order to do this, a brief description of the theoretical fishery model is required.

2.   The fishery model

The literature on economics of exploited fish stocks dates back to the work of Warming in the first half of the 20th century (1911, 1931). Probably because he wrote in Danish, Warming's insights have remained rather unknown to many fishery economists. In the 1950s, the seminal articles by Gordon and Schaefer were published. These helped to clarify/illuminate the distinction between the economics of a fishery characterised by sole ownership on the one hand, and common property on the other hand. In the "sole-ownership" case, one owner controls access to the resource as well as the physical capital needed to harvest its yield. In the opposite case, open-access is characterised by the lack of property rights to the resource. The fundamentally different economic consequences that follow these two institutional arrangements make it natural to deal with them separately.

2.1   Sole ownership

Gordon (1954) and Schaefer (1957) addressed economically optimal exploitation of fish stocks. They combined the knowledge that the growth of a fish stock, and the catch per unit effort in the fishery, both may depend on the size of the stock. Through modelling they derived the optimal effort, yield and stock level. The model developed by Gordon and Schaefer was static, in the sense that it did not discuss the economics of moving from an existing stock/exploitation (irrespective of whether this was

characterised by over- or under utilisation) to the preferred level. Nor did the model discuss the impact of time discounting on the optimal steady state stock and yield.

The latter issue was, however, solved by Clark and Munro (1975), who incorporated capital-theoretic aspects into the model. By the use of Pontryagin's Maximum Principle, they argued that management should aim for a net return rate of the stock at the same level as the prevailing discount rate of the society.

The fundamental principles for optimal fish stock management were further developed in Colin Clark's textbook *Mathematical Bioeconomics* (1976). Assuming infinitely elastic demand (constant prices), equation 3.8 in his book gives the optimal (steady-state) investment policy for the stock. The rule, which is also derived in the appendix to this introduction, is given as:

$$F'(x) - \frac{c'(x)F(x)}{p - c(x)} = \delta \tag{1}$$

where:

$F(x)$: Growth rate of fish stock

$c(x)$: Cost of a unit harvest (unit cost)

p : Price of a unit harvest (unit price)

δ : Discount rate of society

Equation (1) explicitly regards the fish stock as natural capital whose benefits will be maximised if this criterion for optimal portfolio is adhered to. The criterion states that the marginal rate of return from the natural capital (here fish) shall equal the marginal rate of return of other assets in society, here assumed equal to δ. The left-hand side of the equation reflects the return on a marginal investment in the fish stock and consists of two elements. The first element is the marginal growth rate of the stock that depends on the stock itself. The second element reflects the marginal stock effect, or how the optimal stock level is affected by harvesting costs sensitive to the stock level.

The optimal investment policy for the stock is then to keep it at a biomass level where the return on the marginal investment in the stock equals the opportunity cost of capital as represented by the prevailing discount rate of society. Implicitly assuming that fishing effort is a completely variable input factor, Clark shows that the stock should not be harvested if the left hand side of (1) is greater than its right-hand side. Such a moratorium on catch can be labelled a positive investment in the resource. On the other hand, if the prevailing discount rate of society is greater than the left-hand side of equation 1, the stock should be harvested at maximum capacity. This would then be characterised as a negative investment in the resource. Since this effectively implies opening and closing of a fishery conditioned on whether or not the stock is above or below a target level, the policy has been labelled "bang-bang" policy. At the target level, the stock can be harvested at a steady-state rate. Departing from the same assumptions, Reed (1979), confirmed this optimality of a most rapid approach for fish stocks with stochastic recruitment. However, Clark and Munro (1975) have shown that the bang-bang solution is not optimal for non-linearity in costs or prices.

Equation 1 can be extended in different ways, to account for various conditions of price, costs and growth conditions of the fish stock. However, this does not change its fundamental portfolio message.

2.2 Common property

The basic fishery model discussed above assumes that a "sole owner" may select or command the optimal fishing effort, and through that measure establish the optimal stock level and the corresponding yield. As mentioned above, this assumption is seldom satisfied in practical fishery management. The manager is usually one, two or more states or a regional fishery organisation. If the stock is straddling or shared, there must be agreement between the relevant parties on harvest rule and how to allocate the yield. The yield allocated to one party may be distributed within the industry and regulated by measures such as number of vessels, days at sea, gross fishing power or IVQs. In addition to these comes regulation of exploitation pattern to enhance the growth potential of the fish stock.

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In effort-regulated fisheries, management agencies will target stock and yield level by regulating number of vessels, days at sea, engine power, length of vessels etc. Private companies that control the physical capital will have incentives to circumvent such regulation, driven by the forces recognised by Hardin (1968) as "the tragedy of the commons". This has, for a number of fish stocks, made it difficult for managers to implement the insights of the fishery model in practical fishery management. In the Northeast Atlantic, the question of harvest rules for fish stocks and effort level in the fishery have more often than not been dealt with as separate questions. Hence, even if managers are able to establish a harvest rule for the stock, the industry have had incentives to invest in the physical capital to a level at which potential rent from the stock is dissipated.

The fundamental principles of such rent-dissipating investment are quite similar to what can be expected in an open-access fishery. Both Warming (1931) and Gordon (1954) showed that a profitable open-access fishery, if left unregulated, can be expected to attract fishing effort to a level where total costs equal total revenue and no resource rent can be extracted from the fishery. The conclusion is based on an expected profit-maximising behaviour of the firms exploiting the fish stock, and the effect harvest by each firm has on the productivity of the fish stock and consequently future income of the other firms: Each firm will have incentives to increase its effort in the fishery if revenue from the harvest exceeds its costs. As each firm increases its effort, or new firms enter the fishery, total effort in the fishery will increase and the fish stock will be reduced. This process will continue until total costs equal total revenue from the fishery.

Assume then, as in the Northeast Atlantic, that the parties exploiting a fish resource succeed in establishing a harvest rule. Consider further that the harvest rule is implemented by the use of a Total Allowable Catch (TAC), which is allocated with national TACs to the various parties each year. Within each national TAC, management does not control investment in physical harvesting capacity. To the individual firm, profit-maximising incentives will lead to an increase of effort if the revenue from the fishery exceeds its costs. By increasing their effort, the individual firm may increase its harvest, but since the fishery is regulated with a TAC, such an increased harvest will reduce the harvest of the remaining vessels. As in the open-

access fishery, the effort will be expected to increase until total costs equal total revenue[2]. And, as in the open access fishery, rent may be totally dissipated. The only difference from an open-access fishery is that with the TAC regulation, the stock level and its corresponding yield is set by managers, whereas in the open-access fishery, the stock level and the corresponding yield is set by population dynamics of the stock and the economics of exploitation.

Munro and Scott (1985) have labelled such a fishery a "Class II common property fishery". It highlights the need for regulating effort going into the fishery by individual vessel quotas. Where individual vessel quotas (IVQs) have been implemented, they have in some countries been made transferable.

In Norway, the major fisheries are regulated with IVQs, see Årland and Bjørndal (2002). IVQs restrict the output of the single firm to a specific share of the TAC and should, over time, eliminate incentives to increase effort beyond what is necessary to produce the individual firm's output level. When output in an industry is restricted, rational firms should be expected to maximise profits by minimising costs.

3. Stock investment in IVQ-regulated fisheries

In the pure Class II common property fishery, it could be argued that, since all rent can be expected to be dissipated, the question of harvest rule/investment in the fish stock is a non-economic question. In such cases, a change of harvest rule that generates profit will attract effort to the fishery until all rent once again is dissipated (Bjørndal, 1992, page 31). Under such circumstances, the question of optimal stock and yield level is reduced to biological considerations such as keeping stocks at the level where they produce maximum sustainable yield (MSY), or ensuring that they be kept within safe biological limits.

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[2]   In practice, if the regulation of the fishery is restricted to a TAC, profit maximisation may lead to a competition between firms that result in the entire TAC being caught within a short period of time. If the price for the product is sensitive to harvest volumes, this may have severe consequences for the total revenue from the fishery.

However, the IVQ-regulated fisheries differ from the Class II common property fisheries in that firms can be expected to maximise profits by minimising costs rather than by increasing their effort. This should prevent the total dissipation of rent, and is in line with increasing general profitability in the fishery. If, in such fisheries, a change of harvest rule generates a higher economic yield, the IVQs should restrict the firm's incentives to invest in physical capital beyond what is necessary to produce its output. And, if a revised harvest rule increases profitability, either through reduced costs or increased price, the existence of IVQs should eliminate incentives to build up effort to a level where all rent is dissipated.

Thus, an IVQ-regulated fishery creates fundamentally different incentives than what can be expected to exist in a Class II common property fishery. Hence, even though the manager does not control the physical capital needed to harvest the yield, assessment and inclusion of economic relationships, as described by Clark and Munro (1975), becomes highly relevant when making stock investments or formulating harvest rules for fish stocks.

4. Application of the fishery model

The general insights of the fishery model have been applied to various fish stocks in order to find their optimal stock level and corresponding yield. Some of these applications have assumed sole ownership. The results of these analyses show optimal stock level and corresponding yield if the sole owner had had the power to manage the resource and the effort going into the fishery. As such, they are illustrative in showing the potential yield from optimally managed stocks. Below, some of these applications will be discussed.

Focus on growth rates (whales and fish)

Focusing on biological growth (using a Schaefer-model assuming constant prices) Clark (1976, page 49) analyses how optimal stock and yield levels of the Antarctic fin whale depend on the prevailing discount rate of society. Compared to fish stocks,

whales exhibit rather low growth rates. Not surprisingly then, when applying the fishery model, Clark finds that the optimal stock level and yield are highly sensitive to the discount rate of society. He finds that at a discount rate of 20% it would be optimal to reduce the whale population to approximately half the stock size that would yield MSY.

In the same book, Clark analyses optimal stock and yield for the Pacific halibut stock. The growth rate of this stock is far higher than that of whales, and he finds that optimal stock and yield from the fish stock is less sensitive to reasonable levels of discount rates. By comparing the two examples, one conclusion can be drawn: Assuming constant prices and costs, it is economically optimal to deplete a resource whose marginal growth rate is slower than society's social rate of discount.

Pelagic fish stocks with low stock elasticity[3]

In two articles, Bjørndal (1987 and 1988) analyses optimal stock level and corresponding yield in the North Sea herring fishery. Herring (*Clupea Harengus*) is a stock that forms schools, which may imply that the costs per unit catch do not increase as the stock declines. He sets up a production function with the number of boats, number of boat-days, size of boats and the stock size as production factors.

In Bjørndal (1987) it is found that the stock elasticity of output is low. With costs depending on effort, costs per unit catch do not vary much as stock varies, and he attributes this result to the schooling behaviour of the stock. Interpreted with equation 1, this should leave the second term on the left-hand side of the equation small, and (assuming constant prices) the optimal stock level should be close to the level that equalises the marginal growth rate of the stock with the prevailing discount rate of society. It is interesting then, that whether or not costs are included in the analysis matters a great deal as regards optimal stock level.

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[3]   In this dissertation, the term "stock elasticity" refers to either output or unit costs. If the stock elasticity of output is greater than zero, an increase in stock increases output. If the stock elasticity of unit costs is less than zero, an increase in stock size reduces unit costs.

In Bjørndal (1988) it is stressed that, due to the schooling behaviour of pelagic fish stocks, such stocks are vulnerable to extinction. He finds optimal stock size to be "fairly sensitive" to changes in the discount rate.

For pelagic fish stocks, low stock elasticity of output may imply profitable fisheries even at low stock levels. This indicates that, for such stocks, the question of optimal stock level depends more on the relationship between the marginal growth rate of the stock versus the discount rate of society than is the case for demersal fish stocks.

Demersal fish stocks with high stock elasticity

In Schaefer (1957) it is assumed that an increase in stock of 1% will increase catch per unit effort by 1% and consequently, if the costs per unit of effort is constant, lower costs per unit catch. This is often referred to as a stock elasticity of output equal to 1. With a constant price, reduction in stock size will then reduce the profitability of the fishery and this reduced profitability will act as "a brake" against biological overexploitation.

Northeast Arctic cod (*Gadus Morhua*) is a demersal fish stock that is caught with trawl, nets, long line, Danish seine and hooks. Hannesson (1983) estimates the stock elasticity of output for the Norwegian fishery utilising the latter four and finds, depending on the specification of effort, stock elasticities of output that range from 0.37 to 0.85. The highest stock elasticities of output are found for vessels using long-line and nets, and far lower for vessels using Danish seine. Hannesson does not assume sole ownership of the resource, but on the basis of the elasticities found, he concludes that the long-liners and vessels using nets would benefit more from a stock recovery than the others.

However, the stock elasticities of output found by Hannesson do not support the assumption made in the Schaefer function. This is a reminder that [i] output in the fishery are not as sensitive to stock size as assumed in the Schaefer model and, as a consequence, [ii] bionomic equilibrium may be found at far lower stock levels than could have been expected using the assumptions inherent in the Schaefer model.

Lessons to be learned from the empirical literature

The empirical literature on optimal management (here: investment in fish stocks) has shown how the importance of the various factors that determine the net benefit payoff from a fish stock varies considerably across stocks. These differences may stem from different productivity of the fish stocks, different economies of exploitation, or differences in the prevailing discount rate of society. The sole owner of a fish stock may evaluate the characteristic features of the relevant stock and associated fishery and optimise his exploitation.

As mentioned previously, sole ownership of marine fish stocks is not common. However, if access to a fishery is restricted and the participating firms in the fishery are regulated with individual vessel quotas, it will be efficient for a manager to utilise the insights of the fishery model to establish sound harvest rule/investment policy for the fish stock. As for the sole owner, this calls for a proper evaluation of biological dynamics, as well as of economics of exploitation.

Against this background, I will introduce the three essays, and in particular, position them relative to the theoretical fishery model outlined above. The main results of the essays are presented in the section "Results and concluding remarks" at the end of the dissertation.

5.   The essays

The three essays that comprise the dissertation deal with the major Norwegian cod and herring fishery. These fisheries are regulated by the use of individual vessel quotas, and a map of where the two fish stocks are distributed is shown in Figure 1.
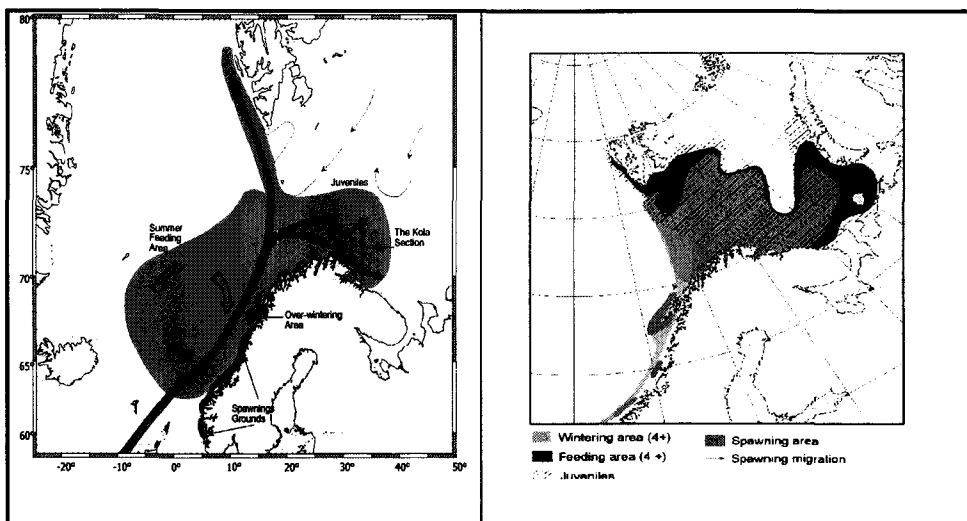
Figure 1   *Area of distribution of Norwegian spring spawning herring (left panel) and Northeast Arctic Cod (right panel).*

The first essay estimates harvest costs in the Norwegian cod and herring fisheries. We ask specifically whether variable unit costs in these fisheries are influenced by either the fish stock or the output/harvest. Hence, we estimate both the stock elasticity and the output elasticity[4] of variable unit costs.

The second essay analyses the economic performance of two different harvest rules for Norwegian spring spawning herring under two different assumptions about price, one in which prices are constant and one in which they are decreasing in output. The rules evaluated are target escapement with a most rapid approach towards the target level and a rule established by the managers of the fish stock characterised by target fishing mortality.

The third essay discusses a particular issue of relevance for the management of a fish stock that becomes straddling at high stock levels. To the parties exploiting the stock this feature is important for critical minimum shares, as well as for the bargaining solution in a cooperative management of the stock.

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[4]   In this dissertation, the term "output elasticity" refers to variable unit costs. If output elasticity of unit costs is greater than zero, variable unit costs increase as output increases.

Essay 1: Estimating variable unit costs in output-regulated fisheries

Optimal investment/harvest rules for the cod and herring stocks, as generally described by equation 1 above, require proper assessment of the population dynamics for each fish stock as well as the economics of exploitation. Essay 1 takes up the latter issue and focuses on the cost of fishing. Total costs of fishing can be divided in fixed and variable costs. Being aware that managers do not control investment, and hence the fixed costs in the fleet, the analysis focuses on variable unit costs that may be directly responsive to changes in harvest rule. The two fisheries come close to two stylised fisheries often encountered in the literature, namely: [i)] a demersal fishery where stock elasticity of output is often assumed to be close to one and [ii)] a pelagic fishery where stock elasticity is assumed to be close to zero.

Harvest rules in output-regulated fisheries will restrict the output from a specific fishery in a given year and affect the biomass of the fish stock in subsequent years. Since individual vessel quotas regulate the vessels operating in these fisheries, the harvest rule will simultaneously restrict the annual output from the single vessel.

The effect that output, as well as stock, might have on variable costs should therefore be assessed when identifying optimal harvest rules. Assuming sole ownership, the rule for stock investment (in steady state) when costs depend on output as well as stock is derived in the appendix and is:

$$F'(x) - \frac{c_x(y,x)y}{p - c(y,x) - c_y(y,x)y} = \delta \tag{2}$$

where :

y : Harvest / output,

and subscripts denote partial derivatives.

Equation 2 explicitly reflects cost as a function of biomass - x - as well as the yield from the biomass - y -. Clark and Munro (1975) discussed this dependence of costs on stock and output, but there have been few empirical investigations of how unit costs are affected by both factors[5].

The contribution of the essay is an empirical assessment of both the stock and output elasticity of variable unit costs. The relationship is estimated for a total of eight Norwegian vessel groups of which three target Norwegian spring spawning herring and five target Northeast Arctic Cod.

Essay 2:   Harvest rules when price depends on quantity

According to Clark (1976), when prices are constant in harvest and harvesting costs are non-increasing in biomass, the optimal harvest rule implies steady state harvesting when the stock is at target level, full use of fishing capacity when the stock is above target level and moratorium when it is below. Reed (1979) analysed whether Clark's result would be invalidated by stochastic elements in the biology of the fish stock, since this would inevitably lead to a stochastic opening and closing of the fishery. He particularly investigated the effect of a stochastic recruitment function, and found that this would imply a target level of the fish stock at or above the target level when recruitment is deterministic. Assuming constant prices, Reed did not, however, find that Clark's conclusion regarding opening and closure of the fishery was invalidated.

When faced with a price decreasing in harvest, Clark and Munro (1975) found that the most rapid approach towards the target level would imply penalties, and that the target escapement level should be approached more asymptotically. In such a case, the optimal rule for stock investment (derived in the appendix) is:

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[5]   In fisheries where output is not regulated, or regulated strictly according to a fixed exploitation rate on an always-correct estimate of the size of the fish stock, it can be assumed that output and stock are perfectly correlated. In such fisheries, it will be admissible to remove output as a regressor. In fisheries where such conditions fail to be satisfied, it is of interest to disclose the relevance of both output and stock as regressors.

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$$F'(x) - \frac{c_x(y,x)y}{p(y) - c(y,x) + \left[p'(y) - c_y(y,x)\right]y} = \delta \qquad (3)$$

Both Reed (1979) and Clark and Munro's (1975) theoretical results are of relevance for practical fishery management. Essay 2 contributes with an empirical assessment of these theoretical results. The case analysed is the Norwegian fishery on Norwegian spring spawning herring. This is a stock with stochastic recruitment and price decreasing in harvest, and the consequences of two different harvest rules are evaluated. The first of these is a target escapement rule with a most rapid approach. The second is a rule based on a target fishing mortality that resembles the asymptotic approach discussed by Clark and Munro (1975).

Essay 3: A small pie for me, or a big one to be shared?

When a fish stock is confined within the exclusive economic zone of one party, the management authorities of that party will be responsible for the investment in the fish stock, i.e. the harvest rule for the fish stock. However, if the fish stock is shared, two or more parties must agree on a harvest rule and the corresponding allocation of the TAC that this rule generates.

Some fish stocks are confined within the exclusive economic zone of one party at low stock levels whereas they become straddling at high stock levels. In general, if the number of players increases as the size of a fish stock increase, this will influence the unilateral optimal stock investment/harvest rule to each party.

Assume that the number of players is a continuous, differentiable function of the stock, labelled $N(x)$. Assume further that the players are identical, in respect of harvesting capacity, price obtained for the fish and the cost of fishing. In that case, the optimal investment rule to each party (derived in the appendix) is:

$$F'(x) - \frac{c'(x)y}{p - c(x)} - \frac{N'(x)y}{N(x)} = \delta \qquad (4)$$

For the case considered in essay 3 (Norwegian spring spawning herring), $N(x)$ is not a continuous differentiable function in which case (4) is modified to

$$F'(x) - \frac{c'(x)y^i}{p - c(x)} = \delta \tag{5}$$

where

y^i is equal to total harvest y divided by number of players N.

Essay 3 provides an empirical assessment of cooperative gains, as well as critical minimum shares, for two parties engaged in cooperative management of a stock that becomes straddling at high stock levels. The case is Norwegian spring spawning herring, and we specifically ask how the critical minimum shares for cooperation changes as the level, at which the stock becomes straddling, changes.

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Appendix   Investment rule for a fish stock

Using the Maximum Principle, Clark and Munro (1975) derived the "Golden rule" for investment in a fish stock where price is constant and costs depend on stock only. The Hamiltonian for the problem is:

$$H = [py - c(x)y]e^{-\delta t} + \lambda[F(x) - y] \qquad (1)$$

where:

p : Price of a unit harvest (unit price)

y : Control variable, harvest or yield

$c(x)$: Cost of a unit harvest (unit cost)

δ : Discount rate of society

$F(x)$: Growth rate of the fish stock

λ : Adjoint variable, expressing the present value of the shadow price of the resource.

The Maximum Principle states that the optimal solution to (1) can be found where $H_y = 0$ and $\dot{\lambda} = -H_x$ where subscripts denote the partial, and the dot above lambda denotes time, derivative. The first of these conditions is a regular first order condition for the Hamiltonian, reflecting that the present value of the shadow price of the resource (λ) shall be equal to the net present value of a unit harvest (see equation 3 below). So, management should ensure that, at every point in time, the value of a unit harvest is equal to the shadow price of the resource.

The second condition, $\dot{\lambda} = -H_x$ or rather $\dot{\lambda} + H_x = 0$ states that the sum of the change in the present value of the shadow price of the resource over time and the change in

the Hamiltonian due to a change in the state variable x shall be zero. Note that changes in x (the state variable) are determined by the control variable y. An investment in the stock will therefore be brought about by a decrease in y. The second condition states that the optimal control implies that any increase (decrease) in H due to a change in state variable x shall decrease (increase) the change in the present value of the shadow price of the resource over time by the same magnitude. An optimal reduction in the control variable y shall therefore ensure that the reduction in H is offset by a corresponding increase in the present value of the shadow price of the resource. If this is not the case, there could exist another control that would increase the economic benefit from the resource, and the control can no longer claim optimality.

Let us first start by finding the first order condition, $H_y = 0$.

$$H_y = [p - c(x)]e^{-\delta t} - \lambda = 0 \tag{2}$$

which implies that

$$\lambda = [p - c(x)]e^{-\delta t} \tag{3}$$

Thereafter, $\dot{\lambda}$ is found as

$$\dot{\lambda} = \frac{d}{dt}[p - c(x)]e^{-\delta t} - \delta\lambda \tag{4}$$

H_x is

$$H_x = [-c'(x)y]e^{-\delta t} + \lambda F'(x) \tag{5}$$

$H_x = -\dot{\lambda}$ implies that

$$\left[-c'(x)y\right]e^{-\delta t} + \lambda F'(x) = \delta\lambda - \frac{d}{dt}\left[p - c'(x)\right]e^{-\delta t} \tag{6}$$

In steady-state, where neither x nor y changes, $\dot{\lambda}$ reduces to $-\delta\lambda$ and by reorganising (6) we get

$$F'(x) - \frac{c'(x)y}{p - c(x)} = \delta \tag{7}$$

The rule states that one should invest in the resource up to the point that the economic return on the marginal investment in the resource is equal to the social rate of discount.

Investment rule when costs depend on stock and harvest

In the same paper, they derive the corresponding golden rule when unit cost depends on harvest as well as stock. The Hamiltonian for this problem is the following:

$$H = \left[py - c(y,x)y\right]e^{-\delta t} + \lambda\left[F(x) - y\right] \tag{8}$$

Let us first start by finding the first order condition, $H_y = 0$.

$$H_y = \left[p - c_y(y,x)y - c(y,x)\right]e^{-\delta t} - \lambda = 0 \tag{9}$$

which implies that

$$\lambda = \left[p - c_y(y,x)y - c(y,x)\right]e^{-\delta t} \tag{10}$$

Thereafter, $\dot{\lambda}$ is found as

$$\dot{\lambda} = \frac{d}{dt}\left[p - c_y(y,x)y - c(y,x)\right]e^{-\delta t} - \delta\lambda \tag{11}$$

H_x is

$$H_x = \left[-c_x(y,x)y \right]e^{-\delta t} + \lambda F'(x) \tag{12}$$

$H_x = -\dot{\lambda}$ implies that

$$\left[-c_x(y,x)y \right]e^{-\delta t} + \lambda F'(x) = \delta\lambda - \frac{d}{dt}\left[p - c_y(y,x)y - c(y,x) \right]e^{-\delta t} \tag{13}$$

In steady-state, where neither x nor y changes, $\dot{\lambda}$ reduces to $-\delta\lambda$ and by reorganising (13) we get

$$F'(x) - \frac{c_x(y,x)y}{p - c(y,x) - c_y(y,x)y} = \delta \tag{14}$$

If unit costs increase as output increases, the output elasticity of unit costs is positive ($c_y > 0$). Relative to unit costs independent of output, such a relationship increases the strength of the marginal stock effect. However, in essay 1 of this dissertation, it is found that $c_y < 0$, possibly due to set-up costs and the fact that the number of trips does not increase proportionally with an increase in the individual vessel quotas. In such cases, the marginal stock effect will be weakened relative to unit costs independent of harvest.

Investment rule when unit cost depends on stock and harvest and price depends on harvest

Now, if, in addition to unit costs depending on harvest and stock, price depends on harvest/output, the Hamiltonian can be written as

$$H = \left[p(y)y - c(y,x)y \right]e^{-\delta t} + \lambda[F(x) - y] \tag{15}$$

$$H_y = \left[p'(y)y + p(y) - c_y(y,x)y - c(y,x)\right]e^{-\delta t} - \lambda = 0 \qquad (16)$$

Thereafter, $\dot{\lambda}$ is found as

$$\dot{\lambda} = \frac{d}{dt}\left[p'(y)y + p(y) - c_y(y,x)y - c(y,x)\right]e^{-\delta t} - \delta\lambda \qquad (17)$$

H_x is already derived in (6), and, $H_x = -\lambda_t$ implies that:

$$\left[-c_x(y,x)y\right]e^{-\delta t} + \lambda F'(x) = \delta\lambda - \frac{d}{dt}\left[p'(y)y + p(y) - c_y(y,x)y - c(y,x)\right]e^{-\delta t} \qquad (18)$$

In steady-state, where neither y nor x changes, (12) reduces to:

$$F'(x) - \frac{c_x(y,x)y}{p(y) - c(y,x) + \left[p'(y) - c_y(y,x)\right]y} = \delta \qquad (19)$$

If unit price decreases and unit costs increase as harvest increases, both will strengthen the marginal stock effect. If both price and unit costs decrease as harvest increases, their combined effect on the optimal stock level depends on their relative strength.

Investment rule for a stock where the number of players increase with stock size

Due to feeding migration, fish stocks will often occupy a larger area at high than at low stock levels. In the case of Norwegian spring spawning herring, the stock was confined within the EEZ of Norway when the stock was at a low level. Feeding migration brought it outside Norway's EEZ at high stock levels. The increased stock implied an increased number of exploiting parties.

Let us for a moment leave the case of Norwegian spring spawning herring and assume a fish stock that increases its area of distribution at large stock levels. Let us further assume that the number of players is a continuous, differentiable function of stock size, $N(x)$. Assume further that all relevant players are equal in the sense that their capacity to fish, the price they receive for the harvest and the harvesting costs are equal. Under such circumstances, the Hamiltonian for the single (identical) player i would be:

$$H^i = \frac{[py - c(x)y]e^{-\delta t}}{N(x)} + \lambda[F(x) - y] \qquad (20)$$

$$H_y = \frac{[p - c(x)]e^{-\delta t}}{N(x)} - \lambda = 0 \qquad (21)$$

$$H_x = \frac{[-c'(x)]ye^{-\delta t}N(x) - [p - c(x)]ye^{-\delta t}N'(x)}{[N(x)]^2} + \lambda F'(x) \qquad (22)$$

$$\dot{\lambda} = \frac{d}{dt}\lambda - \delta\lambda \qquad (23)$$

In steady state, $\dot{\lambda} = -H_x$ will be:

$$\delta\frac{[p - c(x)]e^{-\delta t}}{N(x)} = \frac{[-c'(x)]ye^{-\delta t}N(x)}{[N(x)]^2} - \frac{[p - c(x)]ye^{-\delta t}N'(x)}{[N(x)]^2} + \frac{[p - c(x)]e^{-\delta t}}{N(x)}F'(x) \quad (24)$$

Which, after reorganising, is:

$$F'(x) - \frac{c'(x)y}{p - c(x)} - \frac{N'(x)y}{N(x)} = \delta \qquad (25)$$

With sole ownership at all stock levels, (25) is equal to (1). If $N'(x)$ is positive, it follows that $F'(x)$ must be higher than in the sole owner case and consequently, x must be smaller. As noted above, in the case of Norwegian spring spawning herring, it is not reasonable to believe that $N(x)$ is continuous differentiable. Rather, $N(x)$ can be expected to make a jump from one to several players at critical threshold levels for the stock. Hence, for such a stock, with equal players, the optimal investment rule for the stock will be:

$$F'(x) - \frac{c'(x)y^i}{p - c(x)} = \delta \qquad (26)$$

where

y^i is equal to total harvest y divided by number of players N. In that case, optimal investment can be studied under two different regimes; whether or not the stock is in a straddling state.

Essay 1: Variable unit costs in output regulated fisheries

Variable unit costs in output regulated fisheries

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Abstract

Departing from general cost theory of the firm and bioeconomic theory of the fishery, this paper contributes with an empirical examination of how variable unit costs in a Norwegian demersal and pelagic fishery depend on output and biomass. The identification of the separate effects that the two factors have on costs is not common in the literature. Three Norwegian fleets fishing Norwegian spring spawning herring (*Clupea Harengus*) and five Norwegian fleets fishing Northeast Arctic cod (*Gadus Morhua*) are evaluated. The findings indicate that variable unit costs fall in output in both fisheries. The results also show that variable unit costs fall in biomass in the demersal fishery, but with a stock elasticity of unit costs in absolute terms significantly less than 1. These results are of relevance to a manager seeking the optimal harvest rule and to understand fishermen's incentives when individual vessel quotas are reduced.

1. Introduction

In the Northeast Atlantic, a number of marine fish stocks are managed by harvest rules that specify annual output in the form of a Total Allowable Catch (TAC). The TACs are subsequently broken down by nation, fleet and ultimately as individual vessel quotas (IVQs). This paper addresses how variable unit costs in an IVQ-regulated herring and cod fishery are affected by output and the size of the relevant fish stock. These two fisheries come close to two common stylised fisheries often encountered in the literature as respectively, [i)] a pelagic fishery where the unit costs are assumed to be independent of stock size (Bjørndal, 1987 and 1988) and [ii)] a demersal fishery where the unit costs are assumed to be proportional to the size of the fish stock (Schaefer, 1957).

When unit costs are assumed independent of stock, it is possible to estimate how output affects costs, but the results are critically dependent on the assumption of no stock effect. Likewise, when estimating how costs are affected by stock, it is often implicitly assumed that they are independent of output, an assumption of critical importance for the stock effect measured. In this paper both output and biomass are treated as explanatory variables for costs, and their parameters are estimated simultaneously.

Faced with output controls, the individual firms will have an incentive to minimise costs in order to maximise profits. Incomplete markets for input factors, asymmetric information and skills between the operators of the vessels may, however, lead to large variation in costs, and therefore efficiency, across vessels. Several authors have addressed efficiency questions that involve the use of either stochastic production frontier (SPF) or data envelope analysis (DEA). Kirkley *et al* (1995) have applied SPF to study questions of efficiency in fisheries, whereas Kirkley *et al* (1998) have used the same methodology to assess managerial skill (in a fishery). Grafton *et al* (2000) use SPF to assess efficiency gains of the introduction of individual transferable quotas in a fishery. Coelli (1995) gives a general overview of the method of SPF and DEA. In contrast to the papers by Kirkley *et al*, and Grafton *et al*, the current paper focuses explicitly on how output and stock size affect variable unit costs across vessels in the fishery, regardless of whether the vessels perform on the production frontier.

The motivation for the work is the common knowledge that alternative harvest rules differ in respect of output (quotas) and biomass (fish stock left in sea after harvesting). Such differences will affect both efficient and less efficient vessels. Knowledge of how variable unit costs are affected by output and biomass (the output and stock elasticities of unit costs) has relevance for the choice of optimal harvest rule (e.g. target escapement).

We start out by identifying relevant issues regarding costs in output-regulated fisheries. Panel data drawn from the Norwegian fisheries on Norwegian spring spawning herring and Northeast arctic cod are presented in section 3. The estimation strategy is given in section 4 and results in section 5. Concluding remarks are provided in section 6.

2.   Costs in the fishery

When output in an industry is constrained, dual theory tells us that cost minimisation is a necessary condition for profit maximisation. The cost of production will then depend on the output level, cost function and prices in the input markets.

In the fishery, it is well known that the fish stock is an important production factor, see Gordon (1954) and Clark (1976). Contrary to other input factors, its size is beyond the control of the single firm in the industry and can be considered external. To the fishery, the cost of production therefore also depends on the size of the fish stock. In its most general form, the cost of fishing for a firm can be expressed in symbols as:

$$C = f(W, Y, X, S) \tag{1}$$

where

C : Costs
W : Prices of input factors
Y : Output
X : Biomass of fish stock

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S : Skill of owner/skipper/crew and physical characteristics of vessel

As equation (1) expresses, one of the factors that influences costs in an output-regulated fishery is the output level (Y), or the annual IVQ. At production levels below production capacity, as defined by fixed production factors, it seems reasonable to assume that variable costs to a firm will increase proportionally with the production level. Considering the overcapacity in the Norwegian fishing fleet (and in the world as well, see FAO (1999)), it can be expected that production restrictions usually are set well below production capacity. When production capacity is encountered, one would assume that variable costs would increase at a higher rate than production. Hence, at production levels below production capacity, variable costs per unit should be constant, whereas they should increase once production capacity becomes a constraint.

The existence of variable set-up costs may modify this picture. In the fishery, vessels will be going back and forth between the dock and their fishing grounds. These trips will imply a necessary set-up cost before the harvest process, and the total set-up costs throughout a year will depend on the number of trips necessary to produce the annual IVQ. With incentives to minimise costs, it is reasonable to assume that the length of each trip will be optimised to a specific level. Holding the external production factor (the fish stock) constant, so that catch rates do not vary, the number of trips each year should vary proportionally with the size of the annual IVQ. However, if the number of trips, for some reason or other, increases at a slower rate than an increase in the IVQ (indicating that the vessel will stay longer on the fishing ground at high IVQ than at low IVQ) the variable unit cost in the fishery may be decreasing in output.

The other factor that influences costs is the fish stock (X). The fish stock will influence variable unit costs if its size influences catch rates. An underlying assumption in the model developed by Schaefer (1957) is that there is a direct proportionality between the size of the fish stock and the catch per unit effort (CPUE). The intuition behind is that if a fish stock has a uniform and constant spatial distribution, an increase of the biomass by 10% will increase the density of the stock and the CPUE by the same magnitude. This relation is often assumed in demersal fisheries, and will frequently be referred to as a stock elasticity of output equal to 1.

Holding the output (IVQ) in a demersal fishery constant, this corresponds to assuming variable costs per unit to be proportionally decreasing in biomass, or that the stock elasticity of unit costs is equal to -1.

In schooling species like herring, proportionality between stock size and CPUE is less obvious. In the literature it is either assumed, or found (Bjørndal, 1987, 1988) that there is no, or only a weak, relationship between stock size and CPUE. The intuition behind this assumption is that herring concentrates in schools and thus has no uniform distribution over an area. Once the vessel has targeted a school of herring, the catch during the harvest operation may be unaffected by the size of the fish stock. On the other hand, if a reduction of a herring stock implies that the vessels will spend more time searching for the schools, a relationship between stock size and cost per unit output is to be expected.

Equation (1) further states that cost to the individual firm will depend on prices of input factors (W) and individual effects (S). For the fisheries analysed in this paper it is reasonable to assume that the firms are price takers in the input market, and in the empirical analysis we will assume constant real prices in these input markets.

Individual effects may cause variation in costs across vessels, and be caused either by vessel characteristics or by skill of owner/skipper/crew, see Kirkley et al (1998). It is natural to assume that the vessel characteristics will be fixed for longer periods than the skill of the labour that owns and operates the vessel, but this depends on how often a vessel is sold or a captain or crew is replaced. These differences in costs between vessels caused by individual effects are of special interest when analysing efficiency in the fishing fleet, but they are not of primary interest when assessing how output and stock size affect variable unit costs across vessels in a fishery.

Generally, fisheries may target single species or a blend of species. In the latter case, the vessels can be seen as firms producing several outputs, but where the input factors are the same for each species. Squires and Kirkley (1991) characterise such a multi output production as *"joint in inputs"*. The cost of producing one of the species in a multi-output production may then depend on the production of another species if cost complementarities exist.

Consequently, in a paper analysing the effect of trip quotas[6], Squires and Kirkley (1991) argue that "effective quotas for regulating multiproduct firms require information on the structure of technology and costs". Constraining the catch of one species in a multi-species production will give the firms incentives either to stop fishing, or to continue fishing and discard the regulated species. In a study of a Pacific coast trawl fishery, they found " that when the trip quotas (for sablefish) tighten, the firm cannot sufficiently reorganise its product bundle to preclude increasingly large sablefish disposal" (Squires and Kirkley, 1991, page 122). The authors conclude that inputs to catch sablefish are joint for this and several other species. In a survey article, Jensen (2002) discusses technological and economic features in fisheries and compares results from 12 different studies. Nine of these studies report that production is joint in inputs.

Finally, if the price of fish depends on individual size, an IVQ-regulated fishery may give incentives to discard low-value fish, see Anderson (1994), Vestergaard (1996) and Hatcher (2005).

The Norwegian cod and herring fisheries, whose costs will be evaluated in this paper, differ in respect of technology. In the cod fishery, there may be bycatches of other demersal species, but the quantity of the bycatch is limited. In the herring fishery, there is no bycatch. With the limited bycatch in the cod fishery, the input used in both fisheries will be considered as nonjoint to the production of other species.

3   Data on costs, output (catch) and biomass

Annual cost and catch data at vessel level for the 11-year period 1990-2000 collected by the Norwegian Directorate of Fisheries are used in the estimation. In addition, data on biomasses of cod and herring for the same years are taken from the International Council for the Exploration of the Sea (ICES, 2003).

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[6]   The difference between an annual IVQ, as discussed in this paper, and a trip quota is that the former regulates annual output, whereas the latter regulates output per trip. If catch rates vary at various trips, a trip quota may restrict catches more than an annual IVQ, see Clark (1985).

3.1 Data on costs and output

A panel set of cost and catch data at the vessel level are used. Of all the fleets combined, only a few vessels (14) report cost figures each year, making the data set unbalanced. The vessels are grouped according to fleet, and the fleets are distinguished on the basis of vessel size, gear, or onboard production facilities. Appendix A gives a description of the various vessel groups. Table 1 shows the frequency of reports and the number of observations within each fleet.

Table 1   *Unbalanced panel data set for Norwegian vessel groups fishing Norwegian spring spawning herring and Northeast Arctic cod during the 11-year period 1990 – 2000.*

Frequency	Coastal vessels	Purse seiners	Pelagic trawlers	Coastal vessels below 21 metres	Coastal vessels above 21 metres	Long Liners above 28 metres	Fresh fish trawlers	Factory trawlers
	(herring)	(herring)	(herring)	(cod)	(cod)	(cod)	(cod)	(cod)
1	130	20	30	169	39	20	20	1
2	65	15	22	87	22	13	20	0
3	30	32	8	51	14	19	17	4
4	20	10	6	44	8	10	10	3
5	12	13	6	30	3	4	6	1
6	7	9	5	19	4	5	13	4
7	11	9	3	12	1	7	9	3
8	4	8	4	9	0	1	3	0
9	1	3	0	3	2	2	4	1
10	1	7	0	1	0	3	0	3
11	0	3	0	0	0	1	5	5
Number of vessels.	281	129	84	425	93	85	107	25
Number of observations	660	562	235	1129	221	309	437	169

Operating cost items are defined as items necessary to operate the vessel in the short term. Quasi-fixed cost items are defined as items necessary within a period of a year. The fixed cost items are defined as costs of the vessel (depreciation and financial costs)[7]. In the long run, all these items will be variable and chosen in order to minimise the costs necessary to produce the output. When the output from the vessel is constrained by an annual quota, it seems reasonable to assume that firms will

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[7]   See Table B1 in Appendix B for a detailed classification of various cost items.

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minimise operating costs and costs of quasi-fixed input factors, but how these two cost categories depend on output and biomass levels may differ.

With the exception of labour costs, the market value of each input factor will be used as a proxy for the corresponding opportunity cost. Although wages/share to crew reflect labour cost to the owner of the vessel, these cannot be expected to reflect labour's opportunity cost to society because they vary as a fixed percentage of the value of the catch. Thus, a substitute, based on reported number of man-years utilised on the vessel during a period (a year) multiplied by a figure for the value of a man-year, is used. The actual figure is based on the cost of a man-year in the construction industry (Statistics Norway, 2003).

3.1.1   Data on relevant cost items

From the panel data as shown in Table 1, operating costs and quasi-fixed costs, as identified in Appendix B, were collected. The vessels report these figures annually, and they reflect the annual cost of all fisheries in which the vessel has been engaged. There is consequently a need to disentangle the cost of relevance to the fisheries evaluated in this paper, and the method for doing this is presented in Appendix C. The data span an 11-year period and were normalised to the real price level in year 2000 by the consumer price index (CPI)[8]. Tables B2 and B3 in Appendix B show the annual average values of the sum of operating and quasi-fixed costs in the herring and cod fishery, respectively.

3.1.2   Data on output (catches)

For the panel data described in Table 1, the average catch at vessel level for herring is given in Table B4 in Appendix B. The corresponding figures for cod are given in Table B5.

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[8]   The annual cost items are given in nominal figures. The CPI is a deflator that standardises the purchasing power, and thus the opportunity cost, of using a historical monetary value. Applied on the monetary value of input factors used in the fishery, the CPI thus standardises the opportunity costs of these input factors to society.

3.2   Data on biomass levels

The International Council for the Exploration of the Sea collects time series data on the biomass of cod and herring. In the herring fishery, the fleets are only targeting the Spawning Stock Biomass (SSB). In the cod fishery, coastal vessels target the SSB, whereas the trawlers target a wider range of year-classes, in which case Total Stock Biomass (TSB) is the better measure of the fishable stock. Figure 1 shows the development of SSB of herring and the TSB/SSB of cod for the period 1990-2000. Corresponding figures are given in Appendix B, Table B6.
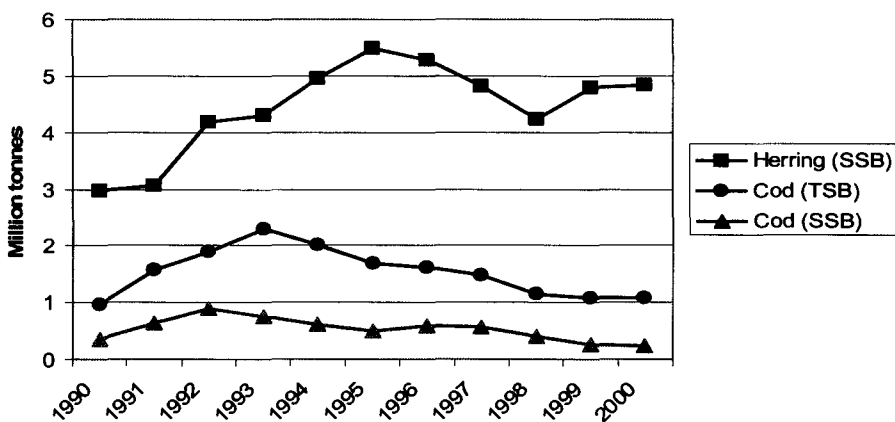
Figure 1   *Development of total stock biomass (TSB) of Northeast Arctic cod and spawning stock biomass (SSB) of herring during the period 1990-2000*

With these data we will proceed to estimate how variable unit costs depend upon output and biomass. The strategy for this estimation is given in the next section.

4   Estimation strategy

As discussed in section 2, the cost in an output-regulated fishery is expected to depend on output, biomass, the price of the input factors, as well as the skills of the owner/skipper/crew and the physical characteristics of each vessel. Assuming constant real prices in the input markets, the functional relationship for the variable costs of an individual vessel can be expressed as:

$$C_{i,y} = f(Y_{i,y}, X_y, S_i) \tag{2}$$

where

$C_{i,y}$: Variable costs for vessel i in year y

$Y_{i,y}$: Catch for vessel i in year y

X_y : Biomass in year y

S_i : Skill of owner/skipper/crew and physical characteristics of vessel

It might be expected that catch (Y) and biomass (X) would be correlated, causing problems of multicollinearity, in which case it will be difficult to estimate independent parameters for catch and biomass. Variance inflation factors (vif) were calculated (see Table 2) and showed generally no serious problems of multicollinearity[9]. This is probably the result of the output regulation in these fisheries. In contrast to an input regulation, the output restriction each year is based on the real-time assessment of the stock and existing objectives set by the managers. The annual assessment of the stock is uncertain and its accuracy improves over time. The data representing biomass in this analysis are drawn from an assessment of the time series 1990-2000 as given in ICES (2003), and they differ quite strongly from what these (spawning) stock levels were assessed to be in real time. In addition, the objectives of the managers resulting in a realised vessel quota may have varied throughout the period. Finally, the vessel quotas will vary according to size of the vessel (Aarland and Bjørndal, 2002).

Both Y and X can be measured, whereas S cannot. If S is correlated with the other explanatory variables, estimation by ordinary least squares (OLS) will yield biased results, i.e. the omitted variable problem. The individual vessel quota for the various species is to a great extent determined by the physical characteristics of the vessel (licensed capacity, length or tonnage). To obtain non-biased estimates of the effects of catch and stock on the cost, the unobserved effect of S needs special treatment.

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[9]   A variance inflation factor (VIF) is $1/(1-R_k^2)$, where R_k^2 is the coefficient of correlation between two explanatory variables. A high VIF indicates problems of multicollinearity.

One way forward would be to include a regressor showing some physical characteristics of the vessel, such as licensed capacity, length or tonnage. This could accommodate effects of the physical characteristics of the vessel, but not effects from the skill of the owner/skipper/crew. Another way forward would be to neutralise the unobserved effect of S by the fixed effect method. In the current analysis, this can be justified because our primary interest is on the effects that output and stock biomass may have on unit costs. This technique is equivalent to assigning dummies for the vessels, an approach that will be used in this paper.

4.1   Identification of variable costs

The variable costs have been described as quasi-fixed and operating costs. Both categories are variable within the time period of relevance for the regulatory tool (a year). The operating costs will occur in each specific fishery, whereas the quasi-fixed costs occur as a consequence of all the fisheries in which the vessel has participated. One should therefore expect that consequences of output and biomass on operating and quasi-fixed costs differ.

To evaluate this, the dependence of either operating costs or the sum of operating costs and quasi-fixed costs on output or biomass levels will be examined.

4.2   Model specification

The focus of this paper is to assess how variable unit costs can be explained by output and the production factor external to the individual firm – the fish stock. If the fish stock (X) is constant, changes in variable costs should be affected by output (Y) only. However, if there is also variation in the fish stock, this may affect catch rates at all output levels. In such a production process, it is reasonable to assume that these

variables affect variable costs multiplicatively[10]. The variable cost of a single vessel in a specific year can then be described as:

$$C_{i,y} = \alpha Y_{i,y}{}^{\beta_1} X_y{}^{\beta_2} S_i{}^{\beta_3} \varepsilon_{i,y} \qquad (3)$$

where:

$\varepsilon_{i,y}$: lognormally distributed error term

To find the unit cost in the fishery, (3) is divided by Y

$$C_{i,y} / Y_{i,y} = \alpha Y_{i,y}{}^{\beta_1-1} X_y{}^{\beta_2} S_i{}^{\beta_3} \varepsilon_{i,y} \qquad (4)$$

which may be written as

$$\dot{C}_{i,y} = \alpha \dot{Y}_{i,y}{}^{\beta_1} X_y{}^{\beta_2} S_i{}^{\beta_3} \varepsilon_{i,y} \qquad (5)$$

The unobserved (fixed) effect of S is removed by dummy technique, so the equation estimated is:

$$\dot{C}_{i,y} = \alpha \dot{Y}_{i,y}{}^{\beta_1} X_y{}^{\beta_2} \varepsilon_{i,y} \qquad (6)$$

Inspection of catch data revealed that for one of the vessel groups, the purse seiners, there was a need to introduce a dummy variable to account for changes in fishing areas. Purse seiners whose homeport are in the southern part of Norway changed fishing areas during the period. When the stock of herring was at a relatively low level (in 1990 and 1991), these purse seiners caught the majority of their annual harvest along the coast of southern Norway. When the stock increased, the fishing areas were

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[10]   Weninger (1998) utilises a translog function to estimate variable cost in a mixed fishery on Surf Clam and Ocean Quahog. A translog cost function is also utilised by Bjørndal and Gordon (2001) when estimating cost functions for the fishery on Norwegian spring spawning herring. The advantage of using a translog cost function is that few implicit restrictions are put on its form, and it allows for modelling second order effects such as elasticity of substitution. The modelling of such effects or a cost function in general is, however, not a key point in the current paper.

moved to the coast of northern Norway. As these purse seiners deliver nearly all their catch to processors in southern Norway or abroad (primarily Denmark), a shift northwards of fishing areas implies higher fuel costs.

Norwegian spring spawning herring is available along the coast of southern Norway during spring (when it spawns) and along the coast of northern Norway during late fall. A change in fishing areas towards the coast of northern Norway thus reflects a change of season for the herring fisheries from spring to late autumn. It is not clear what caused a shift of fishing areas and seasons during the period, but changed effort in other fisheries (capelin and blue whiting) may have been important factors. Nevertheless, for the purse seiners, a dummy variable, d, was entered to take account of the changed area of fishing[11], and for that particular fleet the following equation was estimated:

$$\dot{C}_{i,y} = \alpha \dot{Y}_{i,y}^{\beta_1} X_y^{\beta_2} d^{\beta_3} \varepsilon_{i,y} \qquad (7)$$

In the next section, results of (6) and (7) are presented and discussed.

5   Results and discussion

Table 2 shows the estimated parameters of (6) and (7) when $\dot{C}$ represent the sum of operating and quasi-fixed unit costs. Table 3 shows the corresponding parameters when $\dot{C}$ represents R2 (fuel and lubrication oil) in the herring fishery and R2 and R4 (bait, ice, salt and packing) in the cod fishery. Thus the parameters shown in Table 2 show how changes in output or biomass affect the sum of operating and quasi-fixed unit costs, whereas the parameters in Table 3 show how changes in output or biomass affect specific operating costs per unit. By comparing these sets of parameters it is possible to detect whether exclusion of quasi-fixed costs will influence the parameter values strongly.

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[11]   The dummy variable was given a value of zero for 1990 and 1991, and one for the years 1992-2000.

Table 2   Parameter estimates of $\alpha, \overset{\bullet}{\beta_1}, \beta_2$ and (β_3) in equation 6 and (7). The dependent

variable $\overset{\bullet}{C}$ consists of operating and quasi-fixed costs. $\overset{\bullet}{\beta_1}$ is the output elasticity of

variable unit cost, β_2 is the stock elasticity of variable unit cost and β_3 is the effect

of the dummy variable. Standard error (s.e.) in parenthesis.

Fishery	Fleet	α (s.e.)	$\overset{\bullet}{\beta_1}$ (s.e.)	β_2 (s.e.)	β_3 (s.e.)	Variance inflation factor	R^2
Herring	Coastal	22.00 (2.21)	-0.35 (0.04)	-0.66 (0.17)		1.42	0.76
Herring	Purse seine	16.21 (2.88)	-0.10 (0.03)	-0.52 (0.20)	0.37 (0.13)	4.94	0.40
Herring	Pelagic trawl	17.35 (5.36)	-0.29 (0.08)	-0.43 (0.39)		1.67	0.64
Cod	Coastal, 13-21 m	17.14 (0.65)	-0.48 (0.04)	-0.21 (0.04)		1.00	0.85
Cod	Coastal, 21-28 m	14.67 (0.97)	-0.26 (0.06)	-0.21 (0.07)		1.01	0.79
Cod	Long liners	14.88 (1.46)	-0.28 (0.10)	-0.18 (0.04)		1.07	0.60
Cod	Fresh fish trawlers	18.65 (0.74)	-0.22 (0.04)	-0.50 (0.06)		1.02	0.71
Cod	Factory trawlers	20.33 (1.35)	-0.22 (0.06)	-0.59 (0.09)		1.06	0.58

Table 3   *Parameter estimates of $\alpha, \dot{\beta_1}, \beta_2$ and (β_3) in equation 6 and (7). The dependent variable $\dot{C}$ consists of fuel and lubrication oil in the herring fishery (R2 in Table B1), as well as bait, ice, salt and packing in the cod fishery (cost items R2 and R4 in Table B1). $\dot{\beta_1}$ is the output elasticity of operating unit cost, β_2 is the stock elasticity of operating unit cost and β_3 is the effect of the dummy variable. Standard error (s.e.) in paranthesis.*

Fishery	Fleet	α (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)	R^2
Herring	Coastal	22.87 (2.36)	-0.49 (0.05)	-0.77 (0.18)		0.79
Herring	Purse seine	7.71(3.49)	-0.23 (0.03)	0.02 (0.24)	0.26 (0.14)	0.46
Herring	Pelagic trawl	15.17 (5.80)	-0.47 (0.08)	-0.25 (0.42)		0.71
Cod	Coastal, 13-21 m	13.26 (0.77)	-0.53 (0.05)	-0.08 (0.05)		0.82
Cod	Coastal, 21-28 m	11.48 (1.20)	-0.57 (0.07)	0.13 (0.09)		0.78
Cod	Long liners	14.54 (1.43)	-0.32 (0.10)	-0.26 (0.04)		0.68
Cod	Fresh fish trawlers	15.08 (0.90)	-0.31 (0.06)	-0.31 (0.07)		0.66
Cod	Factory trawlers	15.84 (1.31)	-0.37 (0.05)	-0.26 (0.08)		0.58

The explanatory power of equation (6), measured as R^2, varies between 0.58 and 0.85, whereas the explanatory power of (7), the purse seiners, varies between 0.40 and 0.46. Thus, output and biomass explain between 40 and 85% of the variation in variable unit costs.

When variable unit costs are defined as operating and quasi fixed costs (Table 2) all parameters, except β_2 (the stock effect) for the pelagic trawlers, were found to be significant at the 95% level. When costs are restricted to specific operating costs, all parameters were found to be significant except the dummy variable for the purse seiners and the stock effect for four vessel groups.

Effect of output on unit costs in the herring fisheries

In the herring fisheries, output (Y) is a significant variable in explaining variable unit costs for all vessel groups, although the parameter is low for the purse seiners. Table 2 shows that the parameters have negative signs for all vessel groups, which indicate that the unit variable costs fall in output.

Nøstbakken (2004) found increasing returns to scale for all pelagic fisheries in Norway, and thus excess capacity. The negative sign might therefore be caused by the inclusion of the quasi-fixed costs. Table 3 shows the results of regressions where the quasi-fixed costs and labour costs were kept out of the analysis, and the dependent variable is fuel and lubrication oil only. As shown in Table 3, the sign of the parameter did not change and the absolute value of $\overset{\bullet}{\beta}_1$ increased to a significantly higher level (in absolute terms) for all vessel groups, indicating an even stronger relationship between catch and fuel costs per unit than between catch and the sum of operating/quasi-fixed costs.

As mentioned in section 2, set-up costs in the fishery may lead variable unit costs in the fishery to decrease in output if the number of trips necessary to produce the IVQ increases at a slower rate than an increase in the IVQ. Such a relationship effectively means that trip duration is longer at high IVQ than at low IVQ. Specific knowledge of the fishery indicates that this may have been a characteristic feature for two of the vessel groups fishing herring.

The catches of herring are sold either to plants that process the fish for the consumer market or to plants that produce fish meal and oil. The quality of the fish is much more important in the market for human consumption than in the market for fish meal and oil. For many of the vessels in the coastal and the pelagic trawler fleet, which are not equipped with modern storage facilities, quality can be improved by limiting the catch per fishing trip. During the early 1990s, when the TAC for the stock was at a low level, fishermen were only allowed to deliver their catch for human consumption,

whereas when the TAC increased, this regulation was abandoned. The unit costs falling in catches may therefore be caused by a general shift from trips with low catches destined for human consumption at low quota levels to trips destined for industrial purposes at high quota levels.

The latter provides some explanation for why the unit costs are falling in output for the coastal vessels and the pelagic trawlers. The purse seiners have all had modern storage possibilities and delivered almost all of their catches to the market for human consumption throughout the period (1990-2000). Although the unit costs are falling in output for this vessel group as well, the parameter indicates that this takes place to a much lower degree.

Effect of output on unit costs in the cod fisheries

As in the herring fisheries, variable unit costs are falling in output in the cod fisheries. For four fleet segments, the parameter has a value between –0.22 and –0.28, whereas it is even higher for the coastal vessels with an overall length below 21 metres, see Table 2. Why should the unit costs fall more in output for these rather small vessels than for the others?

One reason might be the inclusion of quasi-fixed costs. For this reason, regressions where the dependent variable only consisted of fuel, ice and bait were performed. The same results were obtained as in the herring fisheries; the sign of the parameter did not change and the absolute value of the parameter grew when quasi-fixed costs and labour costs were excluded, see Table 3. For the two groups of trawlers, and the coastal vessels with length between 21-28 metres, the parameter was significantly higher than in Table 2.

Again, will the number of trips in the cod fishery increase at a slower rate than an increase in the IVQs? With the exception of the factory trawlers, there are no specific reasons why this should be the case for a fleet that by and large delivers fresh fish to

processing plants. Motivated by cost minimisation, the duration of the trips should be independent of the size of the IVQ[12].

A third explanation might be sought in incentives that arise under an output regulated fishery. When a quota regulates a vessel's output, the operator of the vessel will have an incentive to minimise costs. However, the price of cod depends on the individual size of the fish caught, so even under an output regulation, the operator of the vessel may have an incentive to discard low-value fish. Anderson (1994) showed that this incentive exist in an IVQ-regulated fishery if the price differential between high- and low-value fish exceed the cost of sorting, discarding and re-harvest. Vestergaard (1996) analysed how incentives to discard would increase when a previously unregulated fishery was being regulated with non-tradable IVQ. Hatcher (2005) found that the incentive structure (for discarding) in an ITQ-regulated fishery is essentially the same as in a IVQ-regulated fishery.

To understand our results, the following question then seems pertinent: Do incentives to discard low-value fish increase as the level of IVQs is reduced? Following Anderson, a necessary condition for this to be the case would be that as IVQs are reduced, the cost of sorting, discarding and re-harvest is reduced relative to the price differential between high- and low-value fish. So, if either the price differential increases, and/or the cost of discarding and re-harvesting decrease, as IVQs are reduced, the incentives to high-grade should increase.

It is beyond the scope of this paper to do an empirical investigation of this question, but it is not unreasonable that the cost of sorting, discarding and re-harvest may decrease as IVQs are reduced. Recall that the vessels in the cod fishery also participate in other fisheries. As IVQ's in the cod fishery increase, each vessel will utilise more effort to produce its quota. Thus, on an annual basis, less effort will be available for other fisheries. To the extent that effort available in other fisheries is so limited that net income from these fisheries are restricted, the cost of effort in the cod fishery also involves an element of opportunity costs in terms of foregone net revenue

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[12]   If the catch per unit effort decreased, this could of course motivate longer trips, but the fish stock and not the output or IVQ level should then cause such an effect.

from other fisheries. This element of opportunity costs should then decrease as IVQs in the cod fishery are reduced.

If high grading exists, more effort is needed to reach a specific output level. Variable cost per unit (non-discarded) catch will then increase. For the vessel owner, these two contradicting incentives for profit maximisation will imply a trade off between incentives to discard low value fish on the one hand, and to minimise costs, on the other hand. Taking account of the remuneration system in the fisheries, where the payment to the crew is based on a share of the value of the output, the incentive to discard low value fish at low output levels should be even greater. Once hired on a fishing vessel, the real opportunity cost of one's own labour may be very low. The fishermen will then have an incentive to maximise the revenue, implying an even stronger incentive for high grading. All this implies that the number of trips may increase at a slower rate than an increase in IVQ, causing unit variable costs to be decreasing in output.

Effect of biomass on unit costs in the herring fisheries

As mentioned, herring is a pelagic stock forming schools. A common assumption in the literature is that variable unit costs in fisheries targeting schooling species are independent of stock size. However, if vessels spend more time searching for schools of herring at low than at high stock levels, a stock effect may be found (Bjørndal, 1988).

For the pelagic trawlers, our results confirm an assumption of no stock effect, whereas a stock effect is found for the coastal vessels and the purse seiners (see Table 2). When the variable costs are restricted to fuel, Table 3 shows that an assumption of no stock effect is also confirmed for the purse seiners. This indicates that quasi-fixed costs may have caused the stock effect found for the purse seiners in Table 2.

However, the stock effect prevails for the coastal vessels irrespective of whether variable unit costs are covering operating and quasi-fixed costs or only the cost of fuel and lubrication. A much lower geographical range of operation than the two other

vessel groups may cause this. As the name indicates, the coastal vessels operate along the Norwegian coast and it might be the case that a more abundant stock implies more schools of herring entering the waters where the coastal vessels operate, thus reducing these vessels' time spent searching for schools of herring.

Effect of biomass on unit costs in the cod fisheries

When variable costs are set equal to the sum of operating and quasi-fixed costs, a stock effect is found for all vessel groups. The data indicate that unit variable costs are decreasing in biomass. The parameter is estimated to −0.21 for the coastal vessel groups and −0.18 for the long liners, whereas it is substantially larger (in absolute terms) for the trawlers. Since the coastal vessels are using passive and trawlers active gear, one would assume that the stock effect should be higher for the coastal vessels than for the trawlers, but the opposite is found, see Table 2.

It should, however, be kept in mind that X represents spawning stock biomass in the regressions for the coastal vessels, whereas X represents total stock biomass in the regressions for the trawlers. The spawning stock biomass has a seasonal migration pattern where a characteristic feature is that the fish concentrate along the coastline of Northern Norway each spring. This gives rise to a coastal fishery on the spawning cod (the Lofoten fishery), which represents a fishery on a very dense concentration of fish. The total stock does not have this migration pattern, and may therefore be harder to locate for the trawlers at low total stock levels.

For the two groups of trawlers, the stock effects are estimated to −0.50 and −0.59, both significantly lower than 1, as implicitly assumed in the Schaefer model. This reflects that when biomass increases by 10%, variable unit costs decrease by 5 and 5.9% for the two vessel groups. If the cost per unit of effort is constant, this implies a stock-output elasticity of 0.5 to 0.59, which is higher than what Eide *et al* (2003) found (but not significantly so) when estimating harvest functions for 18 Norwegian trawlers harvesting the same species (0.42).

When quasi-fixed costs and labour costs were kept out of the regression, the stock effect is no longer significant for the coastal vessels between 21 and 28 metres. The stock effect is reduced for the coastal vessels below 21 metres and the two groups of trawlers, whereas it increases (in absolute terms) for the long liners.

It is, however, of interest to note that the stock elasticities for all five vessel groups are significantly lower than 1. This implies that when biomass increases, variable unit costs decrease less than proportional to the biomass. The parameters estimated cannot then support the general implication of the Schaefer function: that catch per unit effort should be proportional to the stock size.

Comparison of results for the cod and herring fishery

Cod and herring are two species that differ in many aspects. In relation to a fishery, the most important difference is that cod is a high-priced demersal non-schooling species, while herring is a lower-priced pelagic schooling species. Thus, they are targeted with different gear.

In the herring fishery, the results indicate that variable unit costs are decreasing in output, i.e. the output elasticity of unit costs is negative. The output elasticities for the coastal vessels and purse seiners were found to be higher, and for the pelagic trawlers lower, than those estimated by Bjørndal and Gordon (2001), but the differences were not found to be significant. A negative output elasticity is also found in the demersal fishery for cod. This may be caused by the same factor as described for the herring fishery, but another explanation is an inverse relation between the levels of high grading and IVQ.

Furthermore, apart from one vessel group, the empirical analysis shows that pure operating unit costs are not responsive to biomass for the schooling species of Norwegian spring spawning herring, i.e. the stock elasticity is not significantly different from zero. These results confirm the results of Bjørndal (1987 and 1988). As expected, a stock elasticity different from zero was found in the demersal fishery for cod, but interestingly, at a significantly lower level than one. For the trawlers, the

stock elasticity was found to be higher than what was found in Eide *et al* (2003) (but not significant so). For the coastal fleet and the long-liners, the stock elasticity was generally lower than what was found by Hannesson (1983).

The results indicate that variable unit costs in both fisheries are decreasing in output and that the stock elasticities in the two fisheries are more similar than often assumed in the literature.

6 Concluding remarks

In this paper, the effect of biomass and output on unit variable harvesting costs is estimated on the basis of panel data. The data come close to two stylised fisheries often encountered in the literature, namely a pelagic fishery where unit costs are assumed independent of biomass and a demersal fishery where unit costs are assumed to be inversely proportional to biomass. Within the pelagic fishery, three vessel groups and within the demersal fisheries five vessel groups are analysed. Data are drawn from an 11-year period, during which both output and biomass in the two fisheries have changed considerably. It is found that variable unit cost decrease in output for both fisheries. It is further found that variable unit costs in the cod fishery are decreasing in biomass, but at a rate significantly lower than one. In the herring fishery variable unit costs are decreasing in biomass for one vessel group.

The method applied in this paper specifically addresses both output and biomass as explanatory variables for variable unit costs. This was also done by Weninger (1998), but it is not common in the fisheries economic literature, where one of the two is often analysed. In papers where cost function in the fishery is estimated, an example of which is Bjørndal and Gordon (2001), biomass is assumed constant and variable costs in the fishery are assumed to depend on output, capital and input prices. In papers dealing with harvest rules such as Hannesson (1983) and Bjørndal (1987 and 1988), the cost of a unit effort is assumed to be independent of output, and possible changes in unit costs are assumed to be caused by the fish stock.

As mentioned in the introduction, empirical evaluation of unit variable costs is important when choosing the optimal harvest rule, or target escapement (TE). The target escapement level will generally increase in stock elasticity. If variable unit costs decrease as the stock increases, this will, *ceteris paribus*, tend to increase the TE level relative to the TE level for fisheries where unit costs are constant in stock. Furthermore, if variable unit costs decrease as output increases this will, *ceteris paribus*, tend to move the TE towards the level characterised by maximum sustainable yield (MSY) relative to the TE level for fisheries where unit costs are constant in output. Whether the TE level for the two fisheries analysed here would have been moved when introducing the output and stock elasticities found in this paper will depend upon the biological growth model, as well as to the degree to which prices of the harvest will decrease in harvest.

Both output and stock elasticity differ between vessel groups. This implies that what might be considered the optimal TE level could also differ between vessel groups. In the herring fishery, the differences between output and stock elasticity for the coastal vessels, on the one hand, and the purse seiners, on the other hand, could imply different TE levels. Again, this must be established empirically by the use of a bioeconomic model, which is beyond the scope of this paper.

The negative output elasticities found in the cod fisheries raise several concerns. If these reflect high grading at low IVQ levels, managers should be concerned about the implementation success of IVQs when TACs decline. One policy implication is that monitoring and control should be increased when IVQ declines. Another policy implication would be to reduce the number of vessels allowed to participate in a fishery to keep IVQs stable when TACs are reduced, or, as Vestergaard (1996) suggest, to regulate the length of the fishing season.

The relatively low stock elasticity in the cod fisheries is also cause for concern. Departing from an assumption of stock elasticity at around 1, it has often been assumed that the fishery does not threaten demersal fish stocks. The reasoning is well known: as stocks decline, catch per unit effort decreases and variable costs per unit catch increase up to a point when fishing is no longer profitable, at which level fishing cease and the stock can rebuild. The low stock elasticity found in this paper indicates

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that variable unit costs are only moderately sensitive to stock size, which in turn indicates that a fishery will be profitable at far lower stock levels than at stock elasticities around 1.

In addition to their relevance for the question of optimal harvest rule, the results in this paper shed light on the economics in a fishery on a declining fish stock. The combined effect of a low stock elasticity and a negative output elasticity on a declining stock indicates that the operating profit of the fishery will be positive at lower stock levels than otherwise assumed, and that this profitability could be augmented by high-grading. This corresponds to what Myers *et al* (1997) anticipated as the driving forces in the collapse of 6 Atlantic cod stocks off the coast of Canada.

The results found in this paper thus reflect how variable unit costs in a Norwegian cod and herring fishery vary in response to changes in output and biomass, and may be indicative for how such costs vary in similar fisheries.

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Appendix A   Description of vessel groups

In this appendix, a short description of the various vessel groups and some indicators are given. The abbreviation NSSH represents Norwegian Spring Spawning Herring, whereas the abbreviation NEA represents Northeast Arctic.

Coastal vessels fishing Norwegian spring spawning herring

The coastal vessels are the smallest vessels with an overall length below 27.5 metres. These vessels target both demersal species, such as cod and haddock, as well as pelagic species such as saithe, herring and mackerel. The vessels generally operate close to the Norwegian shore. When fishing on pelagic species like herring and capelin, the vessel uses purse seine technology, while nets, hooks and long line are used when fishing on demersal species like cod and haddock.

Tqble A1   Some physical characteristics of the 281 coastal vessels.

Parameter	Minimum	Mean	Maximum
Gross tonnage	49	176	377
Length overall (metres)	13	20	27
Age (years)	0	21	111
Days at sea	62	274	357
Catch of NSSH (tonnes)	50	622	2,805
Total catch (tonnes)	85	1,151	4,184

Purse seiners fishing Norwegian spring spawning herring

The purse seiners are by far the largest vessels, with the most modern fishery equipment. They primarily fish pelagic species using purse seine technology, but in the fishery for Blue Whiting, the vessels shift technology to pelagic trawl. The purse seiners target a wide range of pelagic species, including mackerel, herring, capelin, horse mackerel, blue whiting and sprat. Their area of operation covers the Barents Sea in the north, the North Sea in the south and the areas west of the British Isles, as well as Icelandic waters in the northwest.

Table A2   Some physical characteristics of the 129 purse seiners.

Parameter	Minimum	Mean	Maximum
Gross tonnage	231	453	2,574
Length overall (metres)	27	55	76
Age (years)	0	27	91
Days at sea	5	284	360
Catch of NSSH (tonnes)	95	2,677	7,632
Total catch (tonnes)	1,735	11,500	35,000

Pelagic trawlers fishing Norwegian spring spawning herring

The pelagic trawlers are generally smaller in size than the purse seiners. Their main fishery targets sandeel, Blue Whiting and Norway pout. In addition to this, they fish herring, mackerel and capelin. Their area of operation is mostly the North Sea, but capelin and herring are caught along the Norwegian coast. In all fisheries they use trawl technology.

Table A3   Some physical characteristics of the 84 pelagic trawlers.

Parameter	Minimum	Mean	Maximum
Gross tonnage	96	295	599
Length overall (metres)	15	33	44
Age (years)	0	29	51
Days at sea	174	311	362
Catch of NSSH (tonnes)	12	755	1,709
Total catch (tonnes)	134	5,697	18,000

Coastal vessels 13-20.9 metres (passive gears) fishing Northeast Arctic cod

This vessel group mainly targets cod, saithe and haddock. The vessels use nets, lines, Danish seine and hooks to gather their catch. According to the mean catch figures shown in Table A4, cod is definitely the most important species, and one would expect availability (stock size) and catch of cod to be important explanatory variables for the cost in the fishery.

Parameter	Minimum	Mean	Maximum
Gross tonnage	11	30	137
Length overall (m)	13	16	21
Age	0	23	90
Days at sea	154	272	364
Catch of NEA Cod (tonnes)	0	111	763
Catch of NEA Haddock (")	3	23	266
Catch of NEA Saithe (")	6	64	591
Total catch (tonnes)	2	260	1,460

Coastal vessels 21-27.9 metres (passive gears) fishing Northeast Arctic cod

Table A5 shows some physical properties of coastal vessels larger than the ones shown in Table A4. They also catch a substantial amount of cod, saithe and haddock, but in addition to this, their total catch indicates large catches of other species. This largely constitutes herring and capelin, which these vessels catch in specific seasons with alternative gear (purse seine). As for the vessels of lengths between 13 and 21 metres, one would expect availability and catch of cod to be important factors for the cost of catching cod.

Table A5   *Some physical characteristics of coastal vessels with length 21 – 27.9 m.*

Parameter	Minimum	Mean	Maximum
Gross tonnage	49	113	264
Length overall (m)	21	24	28
Age	1	22	59
Days at sea	62	272	364
Catch of NEA Cod (tonnes)	41	238	953
Catch of NEA Haddock (")	14	38	244
Catch of NEA Saithe (")	4	105	595
Total catch (tonnes)	148	897	2,789

Long-liners above 28 metres (passive gears) fishing Northeast Arctic cod

The long liners fish mainly off the coast, and in addition to cod and haddock, they fish large quantities of tusk, ling, ocean catfish, saithe and Greenland halibut. Of the latter, large quantities of ling, tusk, Greenland halibut and saithe are caught in areas other than those where NEA cod is distributed.

Table A6   *Some physical characteristics of coastal vessels with length above 28 m.*

Parameter	Minimum	Mean	Maximum
Gross tonnage	100	216	688
Length overall (m)	28	37	51
Age	0	17	42
Days at sea	207	311	356
Catch of NEA Cod (tonnes)	11	306	874
Catch of NEA Haddock (")	0	119	947
Catch of NEA Saithe (")	0	58	439
Total catch (tonnes)	170	1,273	3,398

As can be seen from Table A6, the average catch of NEA cod, haddock and saithe constitutes less than 40% of the total catch, and saithe alone less than 5%. A large part of the remaining 60% of the catch is either caught in other areas than where NEA cod occurs or in other targeted fisheries.

Fresh fish trawlers (vessels catching and delivering fresh fish) fishing Northeast Arctic cod

The fresh fish trawlers' catch of NEA cod, haddock and saithe constitutes nearly ¾ of their total catch on the average. In addition to this, the catch consists of shrimp, redfish and also saithe in the North Sea.

Table A7   Some physical characteristics of fresh fish trawlers (vessels catching and delivering
            fresh fish).

Parameter	Minimum	Mean	Maximum
Gross tonnage	33	280	499
Length overall (m)	18	41	54
Age	0	19	51
Days at sea	112	286	364
Catch of NEA Cod (tonnes)	3	723	2,882
Catch of NEA Haddock (")	2	206	1,168
Catch of NEA Saithe (")	1	626	3,607
Total catch (tonnes)	50	2,149	5,335

Factory trawlers (vessels with onboard processing facilities) fishing Northeast Arctic cod

The fifth Norwegian vessel group catching NEA cod is the factory trawlers. As the name indicates, the fleet process the catch. In addition to NEA cod, haddock and saithe, these vessels target shrimp, saithe in the North Sea and redfish in other areas.

Table A8   Some physical characteristics of factory trawlers (vessels with onboard processing
            facilities).

Parameter	Minimum	Mean	Maximum
Gross tonnage	473	777	1,428
Length overall (m)	49	61	76
Age	1	9	30
Days at sea	163	312	365
Catch of NEA Cod (tonnes)	150	1,383	4,495
Catch of NEA Haddock (")	2	419	1,439
Catch of NEA Saithe (")	7	842	2,636
Total catch (tonnes)	511	4,701	8,107

Appendix B   Data on costs, catch and biomass

Table B1.   *Cost items collected by the Norwegian Directorate of Fisheries and classification into fixed, quasi-fixed or operating costs used in this paper.*

No	Item	Classification
R.01	Operating revenues	-
R.02	Fuel and lubrication oil	Operating
R.03	Special social fees	Operating
R.04	Bait, ice, salt and packing	Operating
R.05	Social expenses	Operating
R.06	Insurance of vessel	Quasi-fixed
R.07	Other insurance	Quasi-fixed
R.08	Maintenance of vessel	Quasi-fixed
R.09	Maintenance/investment in gear	Quasi-fixed
R.10	Unspecified expenses	Operating
R.11	Food	Operating
R.12	Wages/share to crew	Operating
R.13	Estimated depreciation	Fixed
R.14.	Total operating expenses	-
R.15	Operating profit	-
R.16		
R.17	Financial income	-
R.18	Profit on exchange	-
R.19	Total financial revenue	-
R.20	Financial costs	Fixed
R.21	Loss on exchange	-
R.22	Total financial expenses	-
R.23	Net financial items	-
R.24	Profit on ordinary act before tax	-

Table B2   *Average unit variable costs (operating and quasi-fixed costs)*
                  for the three vessel groups fishing Norwegian spring
                  spawning herring. NOK per tonnes.

Year	Coastal vessels	Purse Seiners	Pelagic trawlers
1990	3833	2458	1973
1991	3323	1487	2821
1992	2730	1854	2317
1993	1715	1866	1994
1994	1472	1686	728
1995	1411	1254	785
1996	1634	1198	635
1997	1778	1338	1675
1998	1257	1263	842
1999	1282	1266	968
2000	1311	1248	1173

Table B3   *Average unit variable costs (operating and quasi-fixed costs)*
                  for the five vessel groups fishing Northeast Arctic cod.
                  NOK per tonnes.

Year	Coastal, 13-21	Coastal, 21-28	Long liners	Fresh fish trawl	Factory trawl
1990	19366	9985	10854	9098	12121
1991	15369	5925	13639	9030	8303
1992	8620	6414	9049	6242	7689
1993	9145	6542	8338	4499	7232
1994	7553	5926	8682	4295	5753
1995	7836	6410	8285	4284	5189
1996	6757	6222	8518	4455	6558
1997	5835	4862	7574	5292	7591
1998	8527	6280	9173	6390	9010
1999	9150	7290	9364	6731	10106
2000	9769	9425	9544	7476	14145

Table B4   *Annual average vessel output of herring during the period 1990 – 2000. In tonnes.*

Year	Coastal vessels	Purse seiners	Pelagic trawlers
1990	141	232	96
1991	139	200	97
1992	210	293	114
1993	296	941	230
1994	599	1783	505
1995	574	2827	671
1996	701	3678	896
1997	705	4713	985
1998	1030	4222	1012
1999	1162	4179	1081
2000	1178	4039	1124

Table B5   Annual average vessel output of cod during the period 1990 – 2000. In tonnes.

Year	Coastal, 13-21	Coastal, 21-28	Long liners	Fresh fish trawl	Factory trawl
1990	43	77	132	267	401
1991	53	114	145	206	391
1992	76	157	181	536	874
1993	90	178	255	631	1294
1994	126	242	353	1040	2179
1995	131	329	517	906	1774
1996	151	314	409	856	1657
1997	197	415	475	1185	1887
1998	148	289	340	723	1664
1999	101	215	362	639	1219
2000	74	165	345	500	1181

Table B6   SSB of Norwegian spring spawning herring and TSB/SSB of Northeast arctic cod. In tonnes.

Year	Norwegian spring spawning herring	Northeast Arctic cod	
	SSB	TSB	SSB
1990	2 957 154	963 046	343 489
1991	3 047 216	1 558 196	641 481
1992	4 187 096	1 899 457	892 648
1993	4 300 433	2 291 839	746 595
1994	4 956 846	2 017 694	606 245
1995	5 495 927	1 680 824	500 529
1996	5 268 201	1 609 946	579 385
1997	4 821 384	1 467 101	564 704
1998	4 232 596	1 151 504	388 456
1999	4 775 057	1 075 642	251 988
2000	4 828 711	1 084 258	222 138

Appendix C Allocation of costs to specific fisheries

The data are given annually for a panel of vessels, and they describe the income and cost for each vessel during a year. From these data, variable unit costs across fisheries (averages over the sum of fisheries) can be calculated.

Since the effort used to catch a unit of fish may differ between fisheries, there is no guarantee that the average unit costs across fisheries are identical to the unit cost in one of the fisheries in which the vessel operates. A hypothetical example will illustrate this:

Consider a vessel that during a year operates in two fisheries. These are a mixed fishery for cod, haddock and saithe, on the one hand, and the fishery for herring on the other. If this vessel during a year reports variable costs of NOK 1 million and has caught 100 tonnes of cod, haddock and saithe and 100 tonnes of herring, the average cost per tonne will be NOK 5,000.

Suppose the vessel had operated for 8 months in the mixed cod fishery and 2 months in the herring fishery. Since the cost of operating the vessel mostly depends on time spent fishing, the cost of operating the vessel for a month could be set to NOK 100,000. This implies that the cost in the mixed cod fishery will be NOK 800,000 and the cost in the herring fishery 200,000 NOK. Thus, with the information on time spent in the respective fisheries, the unit costs in the mixed cod fishery would have been NOK 8,000/tonne and in the herring fishery NOK 2,000/tonne.

This example illustrates that to find the unit cost in a specific fishery, it is necessary to know how much effort is expended in each fishery. In the absence of such specified data there is a need for an approximation of how effort is allocated. The approximation used in this paper is based on two steps. First, the number of fishing days for each vessel is allocated evenly across the number of months in which the vessel has shown activity, as registered by sales notes. Second, within each month the number of fishing days is allocated to the respective fisheries in accordance with the catch weight in the respective month.

The number of fishing days spent in the relevant fishery can then be approximated as follows:

$$A = \sum_{j=1}^{M_a} (\frac{B}{M_a} * \frac{Y_j}{C_J})$$

(C1)

where

A   : Days utilised by the vessel in the relevant fishery
B   : Total number of fishing days per year
M_a : Number of "active" months for the vessel in the respective year
Y_j : Quantity of relevant fishery delivered in month j
C_j : Total quantity delivered in month j

This approximation to the number of fishing days in a specific fishery may be biased for two reasons. First, distributing the number of fishing days evenly on the "active months" of the vessel may be incorrect. There may be some "active months" with more fishing days than others. Second, allocating the number of fishing days within each month to the respective fisheries on the basis of catch may be subject to the same kind of error as illustrated in the example above (where this allocation key is used on a yearly basis).

Experiments with the data indicate that these two sources of error are not important in the herring fishery. This statement is based on two observations: First, the approximation gives an allocation of fishing days very close to an independent interview survey conducted by the Norwegian Directorate of Fisheries (1990 – 1996). Second, changing the criteria (Y_j) from quantity to value did not change the average number of fishing days allocated to the various fisheries by more than 4-5%.

The reason why the approximation seems to be good can be found in the seasonality of the fisheries. Once engaged in a fishery, a vessel generally continues to operate in this fishery for periods longer than a month. This implies that, for some months, the fishery of interest is the only fishery conducted, while in other months the vessel will not have been active in the fishery at all. Once fishing days have been assigned to the respective months, the monthly allocation key utilises this feature in the fishery to sort

out which fishery a vessel is engaged in, and allocates effort (fishing days) accordingly.

Essay 2: Harvest rules when price depends on quantity

Harvest rules when price depends on quantity

The case of Norwegian spring spawning herring

(Clupea Harengus L.)

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Abstract

For fish stocks where the unit price of harvest is constant and unit harvest costs are independent of quantity and non-increasing in biomass, regulation based on target escapement with a most rapid approach has been shown to optimise the net present value of harvest to society. This result has also been shown to hold for fish stocks characterised by stochastic recruitment, whereas a more asymptotic approach has been advocated if price depends on quantity. In this paper these theoretical results are empirically investigated. Our case is the Norwegian fishery on Norwegian spring spawning herring, a stock with stochastic recruitment and price decreasing in harvest. For this fishery the theoretical results are verified in that target escapement can no longer claim optimality. At constant prices, the target escapement is found to outperform a more gradual approach, but this comes at a cost of a lower expected spawning stock in the end of the period investigated.

1. Introduction

Regulating catch levels by harvest rules is a widely used management tool in fisheries. Clark (1976) showed that a target escapement (TE) rule is optimal for a fishery characterised by known or deterministic changes in the population parameters of the stock, by unit harvest costs non-increasing in biomass, and importantly, by fish stocks facing infinitely elastic demand. Clark showed that the net present value (NPV) of the fishery is maximised by attaining the target escapement level as rapidly as possible. This implies no fishing when the biomass is below the target level and maximum fishing effort when the biomass is above the target level. This is defined as a "bang-bang" harvest rule and implementation requires only rules setting the conditions for closure of a fishery[13].

Reed (1979) relaxed Clark's strict assumption of known or deterministic changes in the population parameters of the stock and showed that a target escapement rule is optimal for fish stocks characterised by stochastic recruitment. Reed's model assumes fish prices constant in catch level and unit harvest costs independent of biomass. Reed's optimal escapement level is no smaller than the optimal escapement level for Clark's more restrictive case. However, stochastic recruitment causes stock fluctuations around the target escapement level, resulting in stochastic closure of the fishery: a policy that may be hard to implement in practice[14].

The assumption of constant fish prices or, in other words, an infinitely elastic demand is crucial to both Clark and Reed's outcome. Reed acknowledges that the optimality of a target escapement rule may be violated if this assumption does not hold, an insight already made by Clark and Munro (1975). In the latter paper it was shown that, when faced with finite price elasticity, the bang-bang approach implies penalties.

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[13]   Bjørndal (1987 and 1988) applied this bang-bang regulatory approach to the North Sea herring.

[14]   In practise, such a policy would bear substantial adjustment costs as many factor inputs are fixed to the fishery with little or no alternative use. Clark, Clarke and Munro (1979) addressed the consequences of capital lacking malleability for optimal exploitation of renewable resources. In lack of malleable capital (or labour) the authors found the target escapement approach no longer to be optimal. Their results were reflected in Clark's second edition of Mathematical Bioeconomics (Clark, 1990).

In such a case the authors show that the target (stock) level should be approached by an asymptotic rather than a most rapid approach.

The contribution of this study is to empirically investigate these results. To do this, a target escapement rule is compared to an ad-hoc rule defined by fisheries managers under three scenarios: [i] price is constant in catch level, [ii] price is decreasing in catch level, and iii) a relative comparison of performance of the two rules in a depleted stock environment. The rule, defined by the managers, is characterised by target fishing mortality rather than target escapement, and can be seen as an approximation to the asymptotic rule recommended by Clark and Munro (1975) in the case of finite price elasticity.

The comparison is carried out using a bioeconomic model. Data used in measurement and testing are from the Norwegian fishery on Norwegian spring spawning herring (*Clupea Harengus*), the largest pelagic fish stock in the Northeast Atlantic. This fish stock is characterised by stochastic recruitment and price decreasing in harvest.

The paper is organised as follows: First, the fish stock and the fishery is described. Then the bio-economic model is presented. Thereafter results are provided, whereas conclusions are drawn in the end.

2. The fish stock and the fishery

2.1 The fish stock

The Norwegian Spring Spawning Herring is a pelagic fish stock, forming schools. It spawns off the coast of southern Norway during late winter/early spring, and its offspring are transported by the coastal current northwards to the Barents Sea. After spawning, mature herring follow a clockwise feeding migration in the Norwegian Sea, returning to the fjords in Northern Norway in the autumn. Figure 1 shows the distribution of herring.
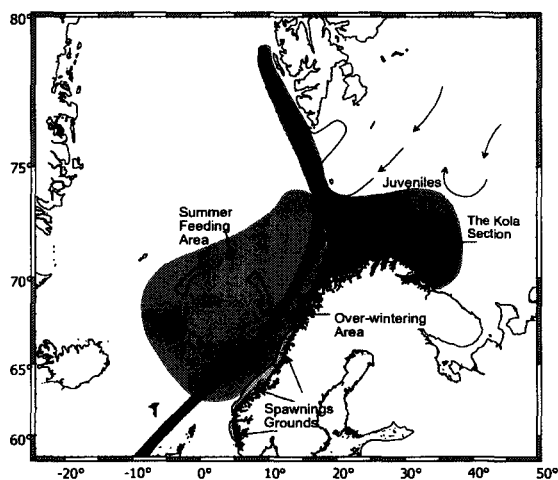
Figure 1.　　　*Migration pattern for Norwegian spring spawning herring. The shaded area shows the current distribution of herring, whereas the black arrows show inflow of warm Atlantic water (the Gulf Stream).*

The size of the spawning stock biomass (SSB) of Norwegian spring spawning herring varies considerably. The International Council for the Exploration of the Sea (ICES) has estimated the SSB in 1950 to 12.7 million tonnes, whereas it collapsed to 0.3 million tonnes in the early 1970s (ICES, 2003a). During the latter half of the 1980s and the early 1990s, the stock recovered. In 2003 ICES reckons an SSB of approximately 5 million tonnes (ICES, 2003b), see Figure 2.
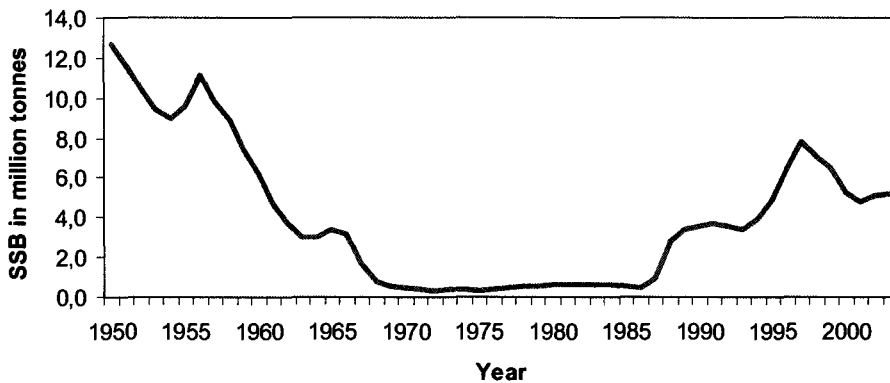
Figure 2   *Spawning stock biomass of Norwegian spring spawning*
                  herring 1950 – 2003.

Figure 2 shows a stock with great fluctuations. In Toresen and Østvedt (2000), the authors conclude that these fluctuations are caused by variations in the survival of recruits, which in turn is caused by environmental factors. Since environment influence on recruitment cannot fully be explained, this paper will treat the influence of the environment as stochastic, see Appendix A.

During the 1960s, vessels with efficient fish-finding equipment maintained a profitable fishery on a rapidly decreasing stock. During this period, the fishery was therefore also a main factor in the deterioration of the stock. Dragesund, Hamre and Ulltang (1980) provide a thorough description of biological characteristics of this herring stock.

2.2   The international management of the fishery

Norwegian spring spawning herring is a straddling fish stock. During its feeding migration, it crosses the Exclusive Economic Zone (EEZ) of several nations. Fishing vessels from the European Union, Faeroe Islands, Iceland, Norway and Russia exploit the stock. Since 1996, these nations, denoted the Parties or the managers, have agreed

to regulate the annual harvest from the stock by a total allowable catch, divided by fixed shares[15].

Since 2001, the total allowable catch has been fixed according to a harvest rule established by the five parties. This harvest rule states that when the SSB is assessed to be below 2.5 million tonnes, the fishing mortality should be 0.05. When SSB is above 5.0 million tonnes, the fishing mortality should be 0.125, and when the SSB is between 2.5 and 5.0 million tonnes the fishing mortality should increase linearly from 0.05 to 0.125. Figure 3 illustrates the harvest rule adopted by the managers.
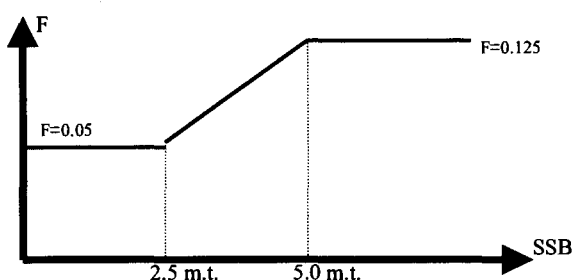
Figure 3   Graphical presentation of a harvest rule where the fishing mortality
                (F) is fixed at 0.125 when the assessed SSB is above 5.0 m.t., linearly
                decreasing to 0.05 when the assessed SSB reaches the level 2.5 m.t.
                and fixed to 0.05 when the SSB is below that level (2.5 m.t.).

Prior to adoption of the rule, its performance was evaluated using medium-term simulations (Bogstad *et al*, 2000). The performance indicators calculated were expected development of catch and spawning stock (including the risk of bringing the stock below safe biological limits of 2.5 million tonnes). However, the expected net present value of the rule was not calculated, nor was the rule compared with a target escapement rule[16]. One obvious difference between the applied rule and a target escapement rule can be seen directly from Figure 3: in the applied rule, the fishery

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[15]   Since the autumn of 2002, the question of allocation has been reopened. Currently, there is no agreement on how to share the TAC.

[16]   Kaitala *et al* (2003) study the performance of alternative harvest rules for Norwegian spring spawning herring. They find a target fishing mortality of 0.14 to give maximum yield. This is quite close to the fishing mortality established by the managers of this stock, at stock levels above 5.0 m.t.

will be open at all stock levels, whereas this will not be the case when following a target escapement rule (with a positive target level).

Assessing the stock and using the ad hoc rule indicates the fishing mortality in a particular year. Subsequently, the TAC is found by multiplying the fishing mortality by the assessed spawning stock. As such, the rule has some of the characteristics of a feedback rule in that the TAC is annually modified by the latest stock assessment. Feedback rules for resource management have been discussed in several papers, see Sandal and Steinshamn (1997 and 2001). For a more thorough discussion of this particular rule, see Røttingen (2003).

The international management of this fish stock is therefore restricted to a harvest rule and an allocation of the resulting quota among the Parties. In addition, there are limitations regarding each Party's access to fish their shares in other Parties' EEZs, and a general minimum landing size of 25 cm. Within these constraints, each Party is free to manage its fishery according to its own national objectives.

2.3   The economics and management of the Norwegian fishery on herring

The Norwegian vessels fishing herring can be categorised into three technologically distinct fleets: coastal vessels, purse seiners and pelagic trawlers. What distinguishes the fleets from one another is the size of the vessels, the range of operation, and to some extent the fishing gear. These technological differences imply that both revenue and costs vary substantially between the fleets (Norwegian Directorate of Fisheries, annual reports) and as shown in Essay 1 of this dissertation.

- The coastal vessels are the smallest vessels, with an overall length below 27.5 metres. These vessels target both demersal species like cod and haddock, as well as pelagic species such as saithe, herring and mackerel. These vessels generally operate close to the Norwegian shore.

- The purse seiners are by far the largest vessels, with the most modern fishery equipment. The purse seiners target a wide range of pelagic species, including mackerel, herring, capelin, horse mackerel, blue whiting and sprat. The area of operation covers the Barents Sea in the north, the North Sea in the south and the areas west of the British Isles, as well as Icelandic waters in the northwest.

- The pelagic trawlers are generally smaller in size than the purse seiners. Their main fishery targets sandeel, blue whiting and Norway pout. In addition to this, they fish herring, mackerel and capelin. The area of operation is mostly the North Sea, but capelin and herring are caught along the Norwegian coast.

For several years Norway has been allocated 57% of the TAC. The distribution of the Norwegian quota among the three fleets follows an allocation key proposed by the fishing industry. The key is dynamic and shown in Appendix C. At low quota levels, coastal vessels are favoured, whereas purse seiners and pelagic trawlers are favoured at high quota levels. The allocation key does not optimise economic revenue from the catch, but is the result of a bargaining process between the vessel groups[17].

The price which Norwegian fishermen obtain for their catch of Norwegian spring spawning herring will be determined by the supply of Norwegian spring spawning herring and a close substitute (North Sea herring) and the demand for the various products derived from these fisheries. The supply of herring from both stocks is regulated by output controls (quotas) that are established annually by the management authorities. The Directorate of Fisheries records prices of the individual landings.

Within each fleet segment, the vessels are regulated through individual vessel quotas. Faced with such an output control, profit-maximising behaviour by the vessel owners will imply incentives to minimise costs. All vessel groups target several species, but the herring fishery is not a mixed fishery. The variable unit costs for each of the three vessel groups fishing Norwegian spring spawning herring were estimated in Essay 1

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[17] Since the economics of harvesting differ between fleets, optimal harvest rules may also differ. Horan *et al* (1999) discuss how distributional considerations may influence the question of optimal harvest rules, but in the current essay, the quota allocation key implicitly give weights to distributional aspects between the three fleets.

of this dissertation and will be used in this paper. These unit costs are non-increasing in both output and stock.

3.   The bioeconomic model

Both aggregate growth models and disaggregated cohort models have been applied in previous papers dealing with Norwegian spring spawning herring. Arnason, Magnusson and Agnarsson (2001) use an aggregated growth function when assessing game theoretic aspects related to the stock[18]. Lindroos (2004) and Bjørndal *et al* (2004) both use disaggregated cohort models in their analysis of other game theoretic aspects of the same stock.

In this paper, the objective is an empirical investigation of harvest rules for a fish stock where one of the natural population parameters – recruitment – is stochastic. In order to capture the stochastic recruitment process, this paper relies on a disaggregated cohort model, outlined in Appendix A.

The measure, to evaluate the consequences of the two harvest rules is the expected net present value, E(NPV) of the Norwegian catch during a period of 50 years. The E[NPV] can be written as:

$$E[NPV] = \sum_{f,y} \{\{P_{f,y}(\bullet) \ - C_{f,y}(\bullet)\} * Y_{f,y} * (1+r)^{-y}\} \qquad (1)$$

where

$P_{f,y}(\bullet)$: average price of herring for fleet $_f$ in year $_y$

$C_{f,y}(\bullet)$: variable unit costs of fishing herring for fleet $_f$ in year $_y$

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[18]   However, when estimating the parameters in the growth function for Norwegian spring spawning herring, Arnason, Magnusson and Agnarsson (2001) do not find them to be statistically valid.

$Y_{f,y}$: catch / quota for fleet $_f$ in year $_y$

$(1+r)^{-y}$: discount factor

The catch, or quota, per fleet per year is determined by the harvest rule, the dynamics of the fish stock, how large a share of the TAC is allocated to Norway, and the allocation between vessel groups. In this paper, the Beverton-Holt model will be used to model Y as a function of the harvest rule. The expected NPV for the Norwegian catch of Norwegian spring spawning herring can then be written as:

$$\text{E[NPV]} = \sum_{y,a,f} \left\{ \{P_{f,y}(\bullet) - C_{f,y}(\bullet)\} * K_f * S * \frac{F_{y,a} N_{y,a}(1 - e^{-(F_{y,a}+M_{y,a})})}{F_{y,a} + M_{y,a}} WC_{y,a} * (1+r)^{-y} \right\} (2)$$

where

$N_{y,0}$: R_y

$F_{y,a}$: fishing mortality (the control variable) directed towards year class (cohort) $_a$ in year $_y$

$WC_{y,a}$: weight of fish (in catch) at age $_a$ in year $_y$

$M_{y,a}$: natural mortality of cohort $_a$ in year $_y$

K_f : fleet specific share of Norwegian quota

S : the Norwegian share of the TAC.

As mentioned in section 2, three technologically different fleets harvest herring. One important technological feature that distinguishes the fleets is the on-board storage facilities for transporting the catch over long distances. The purse seiners have such facilities to a much greater extent than the coastal vessels and pelagic trawlers. We may therefore assume that the catch taken by purse seiners be supplied to a larger market than the catch taken by coastal vessels and pelagic trawlers.

Based on this assumption, separate price functions for each of the three fleets were estimated, see Appendix C, and it was found that the output elasticity of price[19] were - 0.29, - 0.31 and - 0.34 for the three vessel groups. These elasticities were not statistically different between the vessel groups, but they were still used when simulating the E[NPV] of the two harvest rules.

Hannesson (1993) discusses how two different categories of harvest rules (target escapement and target fishing mortality) will imply different levels of optimal fishing capacity and, as a consequence, different levels of fixed costs. Optimal level of fishing capacity is not addressed in the current paper, where the cost figures used reflect average variable unit costs for the three fleets.

A discrete fishing mortality (F) per year is the control variable. For the two harvest rules, F will depend upon the assessed spawning stock biomass as follows:

(1) Target escapement rule

$F = 0$;   when SSB < Target escapement (TE)
$F = F_{te}$;   when SSB > Target escapement (TE)

where F_{te} is the fishing mortality necessary to fish any SSB level above TE down to the TE level during a year. During the 1990s, the annual catches from the stock varied between 0.09 and 1.4 million tonnes. It will therefore be assumed that the annual catches are not restricted by capacity constraints.

(2) Harvest rule established by managers

$F = 0.05$ when SSB < 2.5 million tonnes
$F =$ linearly developing from 0.05 at SSB = 2.5 m.t. to 0.125 at SSB=5.0 m.t.
$F = 0.125$ when SSB > 2.5 m.t.

Both harvest rules are specified with a discrete, (within season) annual fishing mortality, whereas the optimal (target escapement) rule discussed by Reed (1979) was

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[19]   The term "output elasticity of price" refers to how a change in output/harvest affects price. If this elasticity is less than zero, an increase in harvest will reduce price.

given by a continuous fishing mortality[20]. Biological, fishery and economic data are given in Appendix B and C.

Based on the bioeconomic model described above, the expected net present value of the two rules was calculated. Since this indicator depends on the interplay between the rule and the fish stock, it is necessary to evaluate the consequences over a certain time-span. A 50-year period is chosen, which is more than sufficient to include long-term consequences of the rules.

Due to the stochastic recruitment function, 500 replicas of the calculations were performed. Based on these calculations, the expected NPV over the 50-year period as shown in equation (2) was calculated. Even for a period of 50 years large differences in the initial stock will influence the results. To illuminate this aspect the consequences of both rules were simulated on the basis of two different initial stock levels. First, the consequences of the rules when applied to a stock within safe biological limits were analysed and second, the consequences of the rules when applied to a depleted stock were analysed.

4.   Results

The expected net present value, E[NPV] and the expected spawning stock biomass, E[SSB], of target escapement (TE) levels from 1 to 7 million tonnes were evaluated and contrasted with the E[NPV] and the E[SSB] of the ad-hoc rule[21]. First, a comparison was based on constant prices, second on prices decreasing in harvest and finally on the performance of each rule in a depleted stock environment.

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[20]   Since a harvest rule characterised by a continuous fishing mortality may perform better, its discrete version cannot claim to be optimal.

[21]   The interval of 1 to 7 million tonnes covers SSB levels below safe biological limits (2.5 million tonnes) and above the levels where E[NPV] reaches its maximum.

4.1 Constant prices

The level of constant prices was set to the average real price for each fleet during the period 1990-2000. Table 1 shows the E[NPV] and E[SSB] of each rule over a 50-year period[22].

Table 1. *The expected NPV, E[NPV], in million NOK and the expected SSB, E[SSB] in million tonnes of the Norwegian harvest of Norwegian spring spawning herring respectively during and after a 50- year period when applying target escapement from 1 to 7 million tonnes and the rule applied by the managers of the stock. Discount rate set to 5%. 1000 replicates.*

Target escapement	E[NPV]	E[SSB]
(in million tonnes)	Infinitely elastic demand	At end of sim.period
1	8 707	1.0
2	9 264	1.9
3	9 102	2.9
4	8 826	3.8
5	7 952	4.7
6	6 428	5.5
7	5 478	6.4
Ad hoc rule	6 048	6.0

Table 1 shows that when prices are constant, E[NPV] is considerably higher, and the E[SSB] considerably lower, when adopting a target escapement policy than when adopting the ad hoc rule established by the fishery managers. The simulations show that E[NPV] is maximised at a target escapement of approximately 2 million tonnes where the E[NPV] is 53% higher than the E[NPV] when following the ad hoc rule.

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[22] When increasing the target escapement (TE) level, the corresponding E[SSB] at the end of the simulation period is not identical to the TE level, but lower. This reflect that at higher TE-levels, the stochastic recruitment function is not able to fully compensate the withdrawal from the stock which a fishery based on target escapement implies.

Thus, when prices are constant (demand is infinitely elastic), and society has no concern about E[SSB] at the end of the simulation period, Reed's conclusion regarding the optimality of target escapement rules is not challenged by our empirical investigation of the Norwegian fishery on Norwegian spring spawning herring.

As mentioned, the expected SSB at the end of the simulation period is much lower for the optimal TE rule than for the rule established by the managers of the stock. This "mining" aspect explains much of the higher E[NPV] of the TE rule compared to the more asymptotic rule established by the managers of the stock. When applying the latter the E[SSB] at the end of the simulation period is 6.0 million tonnes. The table shows that to obtain the same E[SSB] with a TE rule, the TE would have to be set at some level between 6 and 7 million tonnes. At such a TE level the E[NPV] of the TE rule come close to the E[NPV] of the rule established by the managers. Thus, if society aims for a target value of the stock at the end of the simulation period, for example 6 million tonnes, the two rules are approximately equal as regards the E[NPV].

It should also be noted that if a target escapement rule were adopted, escapement levels between 3 and 4 million tonnes produces E[NPV] in the vicinity of what an escapement level of 2 million tonnes would produce (98 and 95% respectively). To a manager, concerned with stock conservation as an additional objective to maximising expected net present value, this implies the following: as regards Norwegian spring spawning herring, a doubling of the target escapement level from 2 to 4 million tonnes can be achieved at a reasonable (low) cost, equivalent to 5% foregone net revenue during a 50-year period. These TE levels are close to the level which Arnason, Magnusson and Agnarsson (2001) found when evaluating optimal stock size with an aggregate surplus production model (4.2 million tonnes).

As mentioned, the target escapement with a most rapid approach implies a stochastic bang-bang regulation (stochastic opening and closure of the fishery). Figure 4 shows the median, 25 and 5 percentile of forecasted harvest when adopting a target escapement rule (left panel) and the ad hoc rule established by the managers (right panel). In the target escapement rule, the median catch is around 200,000 tonnes (much lower than the mean of 794,000 tonnes), but the variability of the harvest is so

high that the 5% percentiles are beyond the scale from zero to 1.4 million tonnes. This is in sharp contrast to the ad hoc rule, where 90% of the projections imply harvest between 0.1 and 1.3 million tonnes.
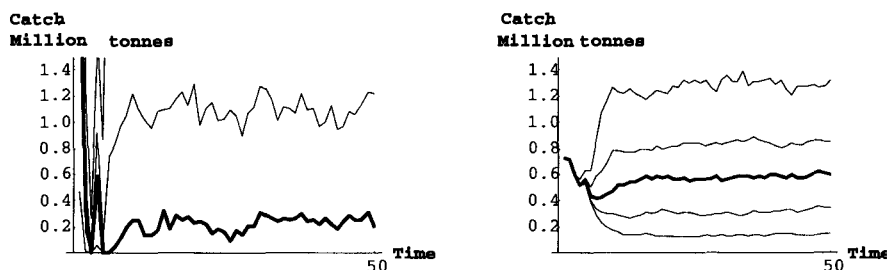

Figure 4   Stochastic forecasts of 500 replicates of harvest per year in a 50-year period. The bold line represents the median, while the thin lines represent the 25 and 5% percentiles above and below the median. The left panel represents the catch forecasts of a target escapement rule at a target level of 5 million tonnes. The right panel represents the catch forecast of the ad-hoc rule established by the coastal states.

The adjustment costs of the stochastic variations in harvest levels will not be dealt with in this paper, but Figure 4 emphasizes another question: Is it reasonable to assume that prices for the product will remain constant for the highly variable catches that a target escapement policy would imply? If not, does the price effect imply that the optimality of a target escapement rule is challenged? We now turn to an empirical assessment of this question.

4.2   Prices decreasing in harvest

When price of harvest depends on quantity, the expected net present value of the various harvest rules falls. This is caused by the average prices in the rules that are severely reduced by the harvest levels[23]. Table 2 shows the E[NPV] and E[SSB] of

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[23]   An additional explanation for the reduced level of E[NPV] in Table 2 relative to Table 1 is the high constant prices applied.

target escapement rules (with various targets) and the ad hoc harvest rule established by the managers of the stock when prices decrease in harvest.

Table 2. *The expected NPV, E[NPV,] (in million NOK) and the expected SSB, E[SSB] in million tonnes of the Norwegian harvest of Norwegian spring spawning herring respectively during and after a 50- year period when applying target escapement from 1 to 7 million tonnes and the rule applied by the managers of the stock. Discount rate set to 5%. 500 replicates.*

Target escapement	E[NPV]	E[SSB]
(in million tonnes)	Prices decreasing in harvest	At end of sim.period
1	1 296	0.9
2	1 631	1.9
3	1 873	2.9
4	2 057	3.8
5	2 072	4.7
6	1 739	5.5
7	1 608	6.4
Ad hoc rule	3 265	5.9

At the output elasticities of price as derived in Appendix C, the optimality of a target escapement rule is challenged by the ad hoc rule established by the managers. For the output elasticity of price as estimated for the Norwegian vessel groups, the expected net present value of the ad hoc rule is 57% higher than the expected net present value of a target escapement rule. Furthermore, the simulations show that when prices are no longer constant, but decreasing in catches, the escapement level that produces highest expected net present value is increased from 2 to 5 million tonnes.

Thus, the simulations show that when price is decreasing in harvest, the target escapement policy is not superior to the ad hoc rule established by the managers of the stock. Although the ad hoc rule implies lower mean catches from year to year than the target escapement rule[24], it mitigates against the adverse effect that the bang-bang regulation has on prices. The ad-hoc rule established by the managers of this fish

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[24]   The simulations show that the mean catch from the ad hoc rule was 734,000 tonnes compared to 794,000 tonnes for the TE rule.

stock implies a much more gradual approximation to the target stock level than do the bang-bang approach. As such, our simulation results provide an empirical verification of the asymptotic approach which Clark and Munro (1975) found to be optimal for stocks where price depends on harvest.

5.   A depleted stock environment

The harvest rules discussed above are specified for the entire range of possible spawning stock levels. However, when the consequences of the two sets of rules were evaluated, the initial level of spawning stock biomass was set to the level assessed in 2003, approximately 5 million tonnes. With such a starting point, the specified stock dynamics and harvest rules applied by the managers will imply a low risk of depleting the spawning stock.

With a stochastic recruitment function, there is a risk of a series of years with bad recruitment. The stock is a schooling species, vulnerable to exploitation even at very low stock levels. Figure 1 showed that once a collapse has occurred, it might take a long period before the stock recovers. In such a depleted stock environment, managers will also be required to manage the resource in accordance with the relevant articles in the Law of the Sea (United Nations, 1982) and the United Nations Fish Stock Agreement (United Nations, 1995). Especially the latter stresses the requirements to manage a straddling fish stock, such as the Norwegian spring spawning herring, with a precautionary approach. In point 5 of Annex II of the United Nations Fish Stock Agreement it is stated that *"If a stock falls below a limit reference point or is at risk of falling below such a reference point, conservation and management action should be initiated to facilitate stock recovery."*

To evaluate how the rules perform to facilitate stock recovery, initial spawning stock was set to its historic level of 0.3 million tonnes in 1975. This level was chosen to mimic a collapsed stock. With this as a starting point, the consequences of a target escapement rule (5 million tonnes) and the harvest rule established by the managers were simulated. The simulation period was set to 50 years and 500 replicates were made. Biological and economic parameters were set as in the appendices with prices

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decreasing in output. Table 3 shows the performance of each harvest rule in relation to four indicators.

Table 3   *Mean catch, expected NPV and SSB at end of simulation period and the probability that the SSB is below minimum biological acceptable level of 2.5 million tonnes during simulation period. Target escapement set to 5 million tonnes.*

Harvest rule	Mean annual harvest	Expected net present value of harvest	Probability that stock will drop below 2.5 m.t.	Expected SSB at end of simulation period
Target escapement	0.26	326	4.3	56 %
Ad hoc rule	0.22	869	4.2	70 %

In a depleted stock environment, table 3 shows that the mean catch over a 50-year period is higher when adopting a target escapement rule than the ad-hoc rule established by the managers. However, when the target escapement rule is applied in a depleted stock environment, the fishery will be closed for a long period. Such closure will not be a feature of the harvest rule adopted by the managers of the stock. In the latter, the fishery will be open even at low stock levels. The small quotas or catch levels generated by the rule will obtain high prices. Thus, the net present value is nearly 2.7 times higher when following the harvest rule adopted by the managers than when following the target escapement rule. So, empirically, the optimality of the target escapement rule with respect to expected NPV does not hold for the Norwegian spring spawning herring either in a depleted or in a non-depleted state[25].

Furthermore, Table 3 shows that at the end of a 50-year period, expected SSB will be slightly higher when applying a target escapement rule with a target of 5 million tonnes than when applying the ad hoc rule established by the managers. The table also shows that the probability that the stock will be below the reference point during the simulation period will be lower when applying the target escapement rule than when applying the ad hoc rule. Figure 5 illustrates this.

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[25]   This result is caused by the prices decreasing in output. Keeping prices constant, the expected NPV of a target escapement was found to be higher than the corresponding value of the ad hoc rule (1,269 and 791 million NOK respectively).
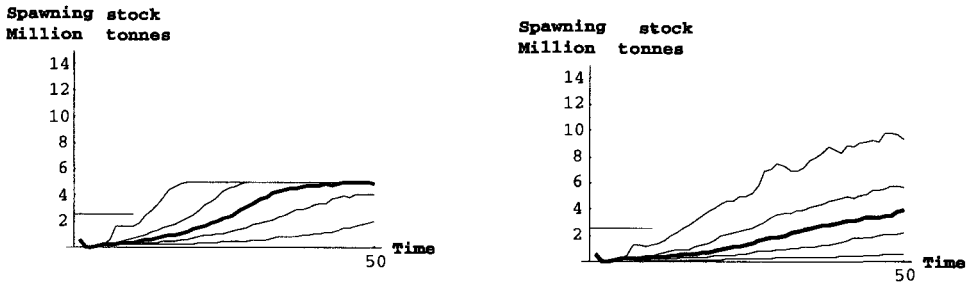
Figure 5   *Stochastic forecasts of 500 replicates of harvest per year in a 50-year period when starting simulations with the stock size as in 1975. The left panel represents target escapement with target level 5 million tonnes. The right panel represents the ad-hoc rule established by the managers.*

Figure 5 shows that the target escapement rule implies a faster stock recovery than the harvest rule adopted by the fishery managers. Concerned both with expected NPV and stock recovery, managers face a trade-off when choosing among harvest rules.

6.   Concluding remarks

The purpose of this paper has been to investigate empirically some previous theoretical results related to what can be considered optimal harvest rules for fish stocks, in particular the results by Clark and Munro (1975), Clark (1976) and Reed (1979). For the fishery analysed, the findings indicate that at the constant price assumption the target escapement rule outperforms the rule established by the fishery managers, but a large part of the higher E[NPV] of the target escapement rules is earned by mining down the stock. If society has the same target for E[SSB] after a simulation period of 50 years, the E[NPV] of the two rules come very close.

When the constant price assumption is relaxed, target escapement can no longer claim optimality. This result was theoretical established by Clark and Munro (1975), and the simulation results of the current paper provide empirical verification to their theoretical result.

This result also holds in a depleted stock environment. However, if, in a depleted stock environment, a most rapid recovery is the only objective for fishery managers, target escapement performs better than the ad hoc rule. Finally, if both expected net present value and stock recovery are relevant objectives, the choice of harvest rule will depend upon the trade-off between the two objectives.

This result makes good intuitive sense: the optimality of the target escapement rule, as established by Clark and Reed, is based on assumptions about infinitely elastic demand and unit harvesting costs independent of quantity and non-increasing in biomass. Under these assumptions, the question of harvest rule is solely dependent upon a comparison between the marginal rate of return from the stock, on the one hand, and the discount rate of the society on the other. If the marginal rate of return from the stock is higher than the discount rate, a closure of the fishery will be the optimal decision and vice versa. Thus, the target escapement level can be found where the marginal rate of return from the stock equals the discount rate of society.

When the assumption of constant prices, or infinitely elastic demand, is relaxed, a market effect becomes relevant when deciding upon harvest rule. Taking this into account, the expected net present value of the harvest will be higher if the harvest can be supplied at quantities that vary less from year to year than they would given a target escapement.

As already touched upon in the introduction, there is another reason for not using target escapement rules in practical fishery management. This is the substantial adjustment cost which the bang-bang consequences of a target escapement policy would imply. The consequences that these costs have on optimal exploitation of renewable resources were theoretically demonstrated by Clark, Clarke and Munro (1979), and empirical verification of their findings should be of interest for future research.

We do not claim that the ad hoc rule established by the managers is optimal, but the simulations show that it is superior to the target escapement rule at the output elasticities of price used in this paper. Another harvest rule whose consequences

would be of interest to evaluate would be a target escapement strategy in which the annual TAC is not allowed to exceed specific levels.

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Appendix A   The biological sub-model

In an age-structured (cohort) model there are four components determining the size and development of a fish stock: Recruitment, individual growth, natural mortality and the fishery. For Norwegian spring spawning herring, recruitment is most variable, and an important element when considering appropriate management measures for the stock.

Recruitment of new year-classes of herring is expected to depend both on the size of the spawning stock and the environment (Toresen and Østvedt, 2000). The influence of the environment makes recruitment stochastic, which implies large variation in the strength of year-classes. Due to this feature, a year-class model represents the stock better than an aggregate surplus production model.

Recruitment, and the subsequent calculation of number of individuals in each year-class during their life span depart from the model developed by Beverton and Holt (1957);

$$R_y = R_{max} * \{X_y / (X_{half} + X_y)\} + \varepsilon_y \tag{A1}$$

where

R_y : recruitment in billions in year y

R_{max} : maximum recruitment

X_y : spawning stock in year y

X_{half} : spawning stock that produced one half of R_{max}

ε_y : normally distributed error term

The effect of the environment on recruitment is incorporated as follows: First, recruitment figures during the period 1950-2002 are divided in two subsets according to whether or not they can be classified as years with a favourable environment. The criterion for a year with a favourable environment is found by first solving equation A1 for X_{half} each year. Low values of X_{half} indicate a year with a favourable environment and vice versa. After ranking the years, 25% representing the best years are put in one subset and 75% in the other. Second, A1 were estimated from each subset of recruitment figures.

Thus, two stochastic recruitment functions are estimated for the stock, one representing generally unfavourable environmental conditions and the other favourable environmental conditions. Third, prognostic recruitment is found by drawing 25% of the replicates from the recruitment function estimated from the subset of data when environmental conditions were good and 75% from recruitment function when the environmental conditions were bad. The effect of the environment is therefore incorporated in two ways; first by the choice of estimating two recruitment functions and drawing prognostic recruitment from them, and second through the error term in each recruitment function. ICES use this method when giving medium term predictions for the stock of Norwegian spring spawning herring (ICES, 2003a).

For each level of prognostic recruitment, the numbers of individuals, can be modelled year by year as:

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \tag{A2}$$

where

$N_{y,a}$: number of fish of age a at the start of year y

$Z_{y,a}$: total mortality rate of age a in year y

y : year

a : age (years)

and

$$N_{y,0} = R_y \tag{A3}$$

Equation (A2) states that the number of individuals N in a cohort a in year y will be reduced with the instant total mortality Z from the current year until the next, $y+1$. Equation (A4) defines the total mortality for a specific cohort in a specific year to be the sum of the fishing mortality and natural mortality.

$$Z_{y,a} = F_{y,a} + M_{y,a} \tag{A4}$$

where

$F_{y,a}$: fishing mortality rate of age a in year y

$M_{y,a}$: natural mortality rate of age a in year y

Equation A5 defines the catch of each year class in numbers of individuals removed from a cohort multiplied with the share of the fishing mortality on the total mortality.

$$C_{y,a} = \frac{F_{y,a} N_{y,a} (1 - e^{-(F_{y,a} + M_{y,a})})}{F_{y,a} + M_{y,a}} \tag{A5}$$

where

$C_{y,a}$: catch in numbers of age a in year y

Equations (A2) and (A5) describe how the number of individual fish in a cohort and in the catch of the cohort develop as a function of natural mortality M and fishing mortality F. To find the biomass of a selected number of cohorts, a summation of the numbers in each cohort multiplied with the average weight of the individual fish is needed. To find the spawning stock (which size is expected to be important for future

recruitment) a multiplication of the numbers in each cohort with the share being mature is needed. Equation (A6) identifies the spawning stock biomass in year y:

$$X_y = \sum_a N_{y,a} WS_{y,a} O_{y,a}, \qquad\qquad 0 \le O_{y,a} \le 1 \qquad (A6)$$

where

$WS_{y,a}$: weight of fish (in stock) at age a in year y

$O_{y,a}$: maturity ogive (proportion of fish at age a which is mature in year y)

The catch each year can now be calculated as the catch of each cohort in numbers multiplied with the average weight in that cohort, as stated in equation (A7).

$$Y_y = \sum_a C_{y,a} WC_{y,a} \qquad\qquad\qquad (A7)$$

where

$C_{y,a}$: catch in numbers at age a in year y

$WC_{y,a}$: weight of fish (in catch) at age a in year y

Given knowledge about the numbers in the recruiting year-classes, the mortality induced by the natural environment, the fishery and the individual weight in each cohort, the biomass of a cohort and the yield from a fishery on that cohort can be calculated. To simulate the biomass of the stock, the spawning stock or the catch from the fishery in a given year, summation of the respective cohorts and yield from the cohorts in that year will be needed.

The relevance of explicitly modelling the fish stock when assessing the economic yield of various harvest rules can be seen through these equations. A harvest rule will imply a specific level of fishing mortality that will reduce the number of individuals

from one year to the next (equation A2). Indirectly, the fishing mortality will also influence the size of the spawning stock (equation A6) and through this future recruitment (equation A1). Equation A7 expresses the physical yield from the fish stock as the product of catch in numbers and weight in catch. Catch in numbers is determined by equation A5, and one has come full circle.

Different harvest rules will therefore lead to alternative development paths for the stock biomass and the yield from the fishery. Both the biomass and the catch will influence the economic yield from the harvest rule.

Appendix B   Biological parameters applied in the simulations

Below, the biological parameters used when simulating the consequences of different harvest rules are given.

Stock in numbers

In the simulations, initial stock in numbers, $N_{y,a}$, given in Equation A2 were set to two different historic stock sizes. These were 1975 and 2003, and are reproduced in Table B1 below:

Table B1   Stock in numbers ($N_{y,a}$) at January 1st in two different years (in billions).

Age	1975	2003
0	2.971	0.000
1	3.467	66.778
2	2.117	1.003
3	0.024	1.374
4	0.000	8.117
5	0.004	9.681
6	0.192	4.296
7	0.000	1.701
8	0.000	0.144
9	0.000	0.417
10	0.000	1.097
11	0.000	2.877
12	0.000	1.700
13	0.000	0.406
14	0.000	0.092
15	0.000	0.050
16	0.986	0.364

Source: ICES (2003b)

Natural mortality, maturity and weight at age

Natural mortality, $F_{y,a}$, as given in Equation 2, vary across age-groups but were set equal across years. Maturity ($O_{y,a}$), and weight at age, both in stock ($WS_{y,a}$) and in catch ($WC_{y,a}$) were set to the values given in Table B2.

Table B2   *Natural mortality, maturity, weight in stock and weight in catch.*

Age	Natural mortality	Maturity (share)	Weight in stock (in kilograms)	Weight in catch (in kilograms)
1	0.90	0.00	0.018	0.018
2	0.90	0.00	0.025	0.025
3	0.15	0.00	0.075	0.075
4	0.15	0.30	0.150	0.150
5	0.15	0.90	0.223	0.223
6	0.15	1.00	0.240	0.240
7	0.15	1.00	0.264	0.264
8	0.15	1.00	0.283	0.283
9	0.15	1.00	0.315	0.315
10	0.15	1.00	0.345	0.345
11	0.15	1.00	0.386	0.386
12	0.15	1.00	0.386	0.386
13	0.15	1.00	0.386	0.386
14	0.15	1.00	0.382	0.382
15	0.15	1.00	0.382	0.382
16	0.15	1.00	0.407	0.407

Source: ICES (2003b)

Recruitment

The parameters in the recruitment function were set to:

Table B3   *Parameters used in the recruitment function. In billions.*

Parameter	Years with favourable environment	Years with unfavourable environment
R_{max}	308.751	242.582
X_{half}	1.626	44.194
Standard error	0.624	1.012

Source: Institute of Marine Research, 2004

Appendix C   Economic parameters applied in the simulations

Allocation of Norwegian quota on vessel groups

The Norwegian quota is allocated to the three vessel groups in accordance with a rule proposed by the Norwegian Fishermen's Union. This rule implies that the allocation will depend upon the Norwegian quota as follows:

Table C.1   *Key for allocating the Norwegian quota to different vessel groups.*

Norwegian Quota (in tonnes)	Coastal vessels	Purse Seiners	Pelagic Trawlers
<20,000	100%	0%	0%
80,000	58%	37%	5%
250,000	48%	44%	8%
500,000	39%	51%	10%
750,000	34.3%	54.7%	11%

Price functions for Norwegian spring spawning herring

The supply of fish is regulated by quotas, which are established annually by the management authorities. The supply is based on biological advice and therefore not responsive to price changes[26]. When a change in supply is followed by a change in price, the latter may be caused by either a movement along a given demand curve or caused by a simultaneous shift in the demand curve. Thus, it is reasonable to assume that the price will be a function of both catch of herring and factors shifting the demand curve. The latter variables may include price developments of substitutes to herring, purchasing power among the consumers in the importing countries, exchange rates etcetera.

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[26]   Nøstbakken and Bjørndal (2003) estimate supply curves for North Sea Herring. For an open-access fishery they find a backward bending supply curve. For an optimal managed schooling fishery they find that supply is inelastic at positive output levels.

In this paper, it is of prime interest to assess how the price of herring is influenced by its supply, since this will have consequences for the expected net present value of various harvest rules. For each of the three vessel groups, the relationship between the average price (in tonnes) of Norwegian spring spawning herring and the global supply of North Sea Herring and Norwegian Spring Spawning Herring were estimated[27]. Data were drawn from the period 1990-2000 (11 observations), which was a period where the global landings of both Norwegian spring spawning herring and North Sea herring have varied considerably. However, focusing on how the supply affects price, one should expect the relationship to suffer from omitted variables.

The relationship between average price and supply of herring was estimated separately for the three vessel groups[28]. Several specifications of the relationship were tested, both linear and log-linear. The following however, was found to give highest explanatory power:

$$P_{f,y} = \alpha Y1_{f,y}^{\beta_1} Y2_{f,y}^{\beta_2} e_f^{\varepsilon} \tag{C1}$$

where

$P_{f,y}$: average price (in tonnes) of Norwegian spring spawning herring obtained by fleet f in year y

$Y1_y$: global landings of Norwegian spring spawning herring in year y

$Y2_y$: global landings of North Sea herring in year y

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[27] In addition to these two herring stocks, the stock of Pacific herring, Baltic herring (ICES subdivision 25 to 29 and 32 minus Gulf of Riga) and Icelandic summer-spawning herring (ICES division Va) produced large catches in the 1990s. The landings of Pacific herring showed large variations during the period, whereas catches from the two other stocks were more stable. It was tested whether the inclusion of global landings from each of these three herring stocks had a significant influence on the price of Norwegian spring spawning herring. This was not found to be the case. For Pacific herring, this indicates that the market for herring from this stock is segregated from the market for Norwegian spring spawning herring and North Sea herring. Concerning herring from Iceland and the Baltic, the limited variations in harvest during the period makes it less obvious to conclude whether or not herring from these areas compete on the same market as Norwegian spring spawning herring and North Sea herring.

[28] Since the regressors are identical for the three vessel groups (global annual landings from the two herring stocks) the parameters could have been estimated through a system of equation by a seemingly unrelated regression model. This would however give the same parameters as when the equations are estimated separately.

e_f : random error, assumed lognormally distributed with zero mean

Table C2 gives the estimated parameters of equation B1.

Table C2   *Parameter estimates of α, β_1 and β_2 in equation C1. β_1 is the output elasticity of price when output is the global landing of Norwegian spring spawning herring. β_2 is the corresponding elasticity when output is the global output of North sea herring. Significance at the 95% level is marked with *. Standard errors in parentheses.*

Fleet	α (s.e.)	β_1 (s.e.)	β_2 (s.e.)
Coastal	19.21 (3.86)*	-0.31 (0.07)*	-0.60 (0.23)*
Purse seine	18.08 (3.17)*	-0.29 (0.06)*	0.50 (0.19)*
Pelagic trawl	19.75 (5.47)*	-0.34 (0.10)*	-0.61 (0.33)
R^2	0.73	0.80	0.65

In the simulations, the catch of North Sea Herring was set to 509.000 tonnes, equivalent to the average catches in the period 1990-2000. Figure C1 shows the estimated relationship between price and global landings of Norwegian spring spawning herring.
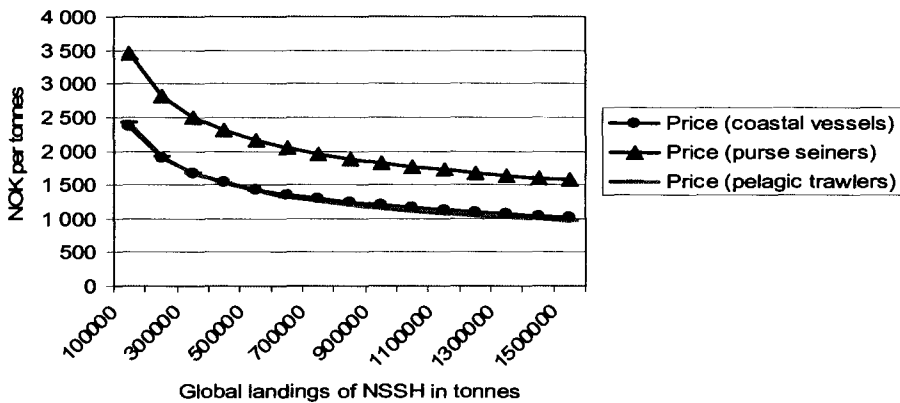
Figure C1   *Annual average price of Norwegian spring spawning herring as a function of global landings..*

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All price functions were tested for omitted variables, heteroscedasticity and autocorrelation. The null hypothesis of no omitted variables were, at the 95% level, rejected for the coastal vessels, but not for the purse seiners and the pelagic trawlers. The tests did not indicate problems of heteroscedasticity or autocorrelation.

Fixed real prices per fleet

The fixed real prices used in the analysis were the historical averages over the period 1990-2000 as given in Table C3. The estimated prices as shown in Figure C1 are at the same level as these fixed prices when global landings of North sea herring are in the range 300 – 500,000 tonnes.

Table C3   Real average prices per fleet during the period 1990-2000,

Fleet	NOK/Tonnes
Coastal	1,655
Purse seine	2,221
Pelagic trawl	1,468

Essay 3: A small pie for me, or a big one to be shared?

A small pie for me, or a big one to be shared?

The management of a fish stock that becomes straddling

at high stock levels

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Abstract

The management of a fish stock that becomes straddling at high stock levels is analysed. For such fish stocks, relevant parties' incentives to stick to a cooperative solution depend, on the one hand, on their share of the cooperative harvest and, on the other hand, on the stock dynamics, the economics of exploitation, and whether or not the stock is in a "straddling" state: The paper first analyses the aggregate benefit of a cooperative solution. Thereafter, cooperative sharing agreements based on the Nash bargaining solution are calculated. Norwegian spring spawning herring (*Clupea Harengus*) is the case studied, and substantial cooperative benefits exist for this stock. The Nash bargaining solution are found to be highly sensitive to the level at which the stock starts to straddle.

1. Introduction

Some fish stocks show a distribution pattern that is dependent on stock size, being confined within the Exclusive Economic Zone (EEZ) of one party when the stock is small, but straddling outside and into the high seas, or the EEZs of other parties, when the stock is large. This raises the question: Is it in the interest of the party that "host" the stock within its EEZ at low stock levels to maintain the stock at such a level where exclusive harvesting rights are secured? Or, would it be better for such a party to maintain the stock at a level where it straddles, but where the annual yield must be shared with others?

The current paper deals with this question. As such, the paper belongs to the literature discussing game-theoretic aspects related to the management of transboundary fish stocks. Key questions in this literature have been the distribution of benefits arising from a cooperative versus a non-cooperative management and stability of cooperative arrangements. The latter typically demands analysis of incentives of individual players to defect from cooperation, as well as credible punishment of defectors by remaining players. When expected costs of a credible punishment are higher than expected benefits of defecting from a cooperative agreement, the agreement is self-enforcing and vice versa. Lindroos and Kaitala (2001) provide an overview of this literature.

The likelihood of reaching a cooperative form of management for transboundary fish stocks thus depends on numerous factors. Munro (1979) was among the first to recognise that when fish stocks are trans-boundary, different regulatory bodies (usually two or more different states) may have diverging social rates of discount, fishing effort costs, or consumer tastes. Lacking side payments, such differences will imply that various parties' views on optimal management will differ. Kaitala and Lindroos (2004) show that timing may be important for whether or not to cooperate.

Hannesson (1997) analysed which factors tend to sustain cooperative management and found that a low (high) discount rate, a small (large) number of parties and a high (low) cost of fishing would make cooperative management more (less) likely.

Several papers have dealt with how (limited) access may influence incentives to cooperate among the parties harvesting a fish stock. Assuming a uniformly distributed stock, Hannesson (1997) illustrates two different cases. In one of these, each identical player has sole access to a share of the area where the stock is distributed. This condition reflects a stock that is distributed across the EEZs of more than one nation, where each nation has exclusive access to harvest the resource in its own zone. Assuming limited migration of the stock between the areas, he finds such designated access rights to increase the likelihood of cooperation relative to a stock where all players have access to the stock over its entire area of distribution. In the second case, a dominant agent has access to the largest area where the stock is distributed, whereas a competitive fringe controls the remaining area. In this case, he finds that the existence of a competitive fringe reduces the optimal stock level, as well as the corresponding net present value (NPV) of the harvest[29].

Arnason et al (2001) discuss the benefit of cooperation through the use of a surplus production model in which prices are constant and harvest costs depend on the stock, harvest and distance to the exploitable biomass. They investigate a number of different non-cooperating coalitions which only have access to the stock on the High Seas and in their own EEZ. In this way, limited access influences the incentives to cooperate via the cost function. Bjørndal et al (2004) show that it is unprofitable for Norway to fish down the stock of Norwegian spring spawning herring to a level where it does not migrate (assumed to happen at a spawning stock level of 0.5 million tonnes).

Hannesson (2004), an empirical extension of Hannesson (1997), also focuses on the Norwegian spring spawning herring. In the 2004 paper, Norway is the dominant player, and herring has its major distribution in the Norwegian EEZ. At high stock levels, part of the herring migrates out of the EEZ where a competitive fringe harvests what is available. Irrespective of this, he finds that Norway would have an incentive to manage the stock at a level where a fraction of the stock migrates to be harvested by the fringe. Hence, this non-cooperative management of the stock does not develop

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[29]   The existence of the competitive fringe will reduce the growth potential of the stock, as available for the dominant agent. With a constant discount rate this will motivate the dominant agent to reduce his target escapement and thus increase the marginal growth rate of the stock.

into an "open access" fishery because the competitive fringe cannot harvest more than the share of the stock available to it.

The literature discussed above has explored how access to the resource and different economic conditions between utilising parties influence incentives to exploit the fish stock cooperatively or non-cooperatively. The main results are that differences in the economics of exploitation will affect both what can be considered an optimal harvest rule and, consequently, the likelihood that a cooperative agreement can be reached, and be self-enforcing.

In general, the literature is based on a static distribution of fish stocks. The contribution of this paper is to relax this assumption by allowing the distribution to be dynamically dependent on the size of the fish stock. Specifically, we ask how the level at which a fish stock changes distribution and becomes straddling influences [i] the critical minimum shares required for a cooperative agreement to be self-enforcing and [ii] an incentive-based sharing key in such an agreement. In general, this specific aspect is important for the likelihood of reaching cooperative agreements in the exploitation of biological resources where user rights are area-based, but the distribution of a stock depends on its (biomass) level[30].

We shall make use of an age-structured bioeconomic simulation model. In this model harvest regulates stock size and, through this, biological productivity and distribution. Once the stock is straddling, we assume that the entire fishable biomass is vulnerable to exploitation by other parties (in addition to Norway).

The paper is organised as follows: First, the aggregate benefit of a cooperative form of management will be evaluated. Then, critical minimum shares, as well as an incentive-based sharing key, will be calculated. Next, the sensitivity of the minimum shares and the incentive-based sharing key are analysed for various assumptions about the level at which the stock becomes straddling. The sensitivity of the sharing key will finally be tested against assumptions about price and discount rates.

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[30] Benchekroun and Van Long (2002) analyse game theoretic aspects for a fish stock where user rights are area-based and the fish stock has an annual migration between these areas. Harvest by the first player will then influence the stock size available for harvest by the second player, and both players will take account of this aspect when optimising their fishing effort.

2. The fishery and its management

Norwegian spring spawning herring is currently the largest pelagic fish stock in the Northeast Atlantic. For more than a hundred years, this stock has been subject to large fisheries by vessels from the states around the Northeast Atlantic, first and foremost Iceland, Norway and Russia. During the 1950s and the 1960s the fishery, combined with unfavourable natural conditions, nearly led to an extinction of the stock and the fishery was closed for several years (Holst *et al*, 2004). The fishery was reopened at a very low level, but increased in the late 1980s and early 1990s when natural conditions favoured growth of the stock.

Traditionally, the stock has migrated extensively throughout the Northeast Atlantic, but its migration pattern has changed through history, see ICES (1995-2004) and Sissener and Bjørndal (2004). During the period when the stock was at a low biomass level (1970-1990) the fishable, or mature, part of the stock was distributed within what is now the EEZ of Norway,[31] whereas larvae and immature herring have occurred in the Russian EEZ as well.

Currently, the spawning stock has a feeding migration that brings it beyond the EEZ of Norway during the May-July period each year. This feeding migration started in 1993/1994 and opened for the possibility of exploitation by other nations than Norway. The red arrow in Figure 1 schematically shows the feeding migration. This development prompted the need for international agreement management measures, first and foremost related to the annual level and allocation of a Total Allowable Catch (TAC).

After several rounds of negotiations, where arguments such as historical fishing rights, the stock's attachment to various EEZs, the scientific contribution of the various parties and various other factors had been evaluated, the coastal states

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[31]   The EEZ of Norway was established January 1, 1977.

managed to agree on how to allocate annual harvest in 1996. The agreement gave Norway a 57% share of the TAC, and other parties 43%. In 2001 the parties agreed on a harvest rule. The rule stated that the annual TAC should be set according to a fishing mortality to be determined by the annual assessed stock size, see Røttingen (2003). However, in 2002 the question of allocation was reopened when Norway claimed a higher share of the TAC than what it had been allocated in 1996. The dispute is currently (2005) not resolved.
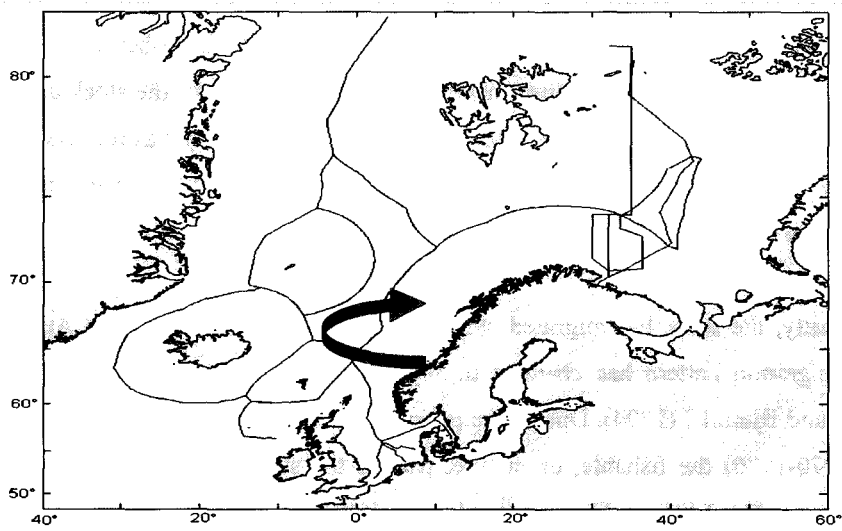
Figure 1   Demarcation of the exclusive economic zones (EEZ) and the High Seas of the Northeast Atlantic. Red arrow indicates migration pattern of Norwegian spring spawning herring at currently high stock levels.

Since the question of allocation is currently unresolved, the harvest rule established in 2001 is not limiting the total annual catch. However, it is interesting to note that no party has explicitly expressed misgivings about the rule, and consequently, ICES applies it when giving advice on the annual catch level for the stock. For 2005, Norway set a unilateral quota for the Norwegian fishery on Norwegian spring spawning herring. In the press release that was given when the quota was fixed, it was stated that the Norwegian quota was fixed with reference to the TAC recommended by marine scientists (Norwegian Ministry of Fisheries and Coastal Affairs, 2005). By comparing the unilaterally set quota for Norway with the recommended TAC for the

stock, Norway has implicitly stated that, for 2005, its share of the TAC should be 65%. This is a share that is 8% higher than what Norway was allocated in 1996, and an increase of its own share of approximately 14%.

After Norway had announced its unilaterally set quota, Iceland set a unilateral quota that was 14% higher than what it would have got according to its allocation from 1996[32]. It is currently not known what the remaining parties will do, but if they follow suit, the relative shares between the parties, as established in 1996, will remain intact. If the parties harvest their unilateral quotas, the total harvest will exceed the recommended TAC.

A factor that influences harvest by each party is the distribution of the stock, and the lesson taught by history is that there seems to be a connection between the stock size and its feeding migration and distribution. At low stock levels the mature part of the stock seems to be confined to the Norwegian zone, whereas the entire spawning stock becomes straddling at higher stock levels. In the straddling phase, the stock has proven extremely vulnerable to fleets from other nations. This implies that once the stock is straddling, it is vulnerable to any exploitation the international fleet may find appropriate. Unlike the assumptions made in Hannesson (1997 and 2004) about a small competitive fringe that only has access to a small share of the resource, in this paper, the fishing effort mobilised by other parties utilising the stock is assumed to be unlimited[33].

Currently, the stock is in a biologically sound condition, but is not managed cooperatively due to the dispute regarding allocation. This lack of cooperation may evolve into excessive harvesting which will deplete the fish stock and waste the economic benefit of cooperation. We shall now turn to an assessment of these benefits.

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[32]   The Icelandic quota for Norwegian spring spawning herring in 2005 is fixed to 157,700 tonnes (Icelandic Ministry of Fisheries, 2005).
[33]   Although history has shown us that the stock either is confined within the EEZ of Norway or has a size where it migrates beyond this EEZ, it is quite plausible that there may be future states of the stock in which only a part of the spawning stock migrates out of the EEZ, or in which the annual period of migration is so limited that the fishing mortality of the other parties will be bounded, as assumed in Hannesson (1997 and 2004).

3. The benefits of cooperation

In order to model the benefits of cooperative management, a bioeconomic model will be utilised. This model is based on the age-structured biological model in Essay 2 of this dissertation.

We shall start by finding the optimal cooperative harvest rule. In order to ensure similarity to the majority of the rules used in fisheries management around the Northeast Atlantic, and to avoid "bang-bang" consequences, it will be assumed that this rule is characterised by constant fishing mortality rather than target escapement[34]. The optimal harvest rule will therefore be found by optimising the Net Present Value (NPV) with respect to a constant fishing mortality.

3.1   The cooperative solution

There are currently five parties exploiting Norwegian spring spawning herring. These are the EU, Faeroe Islands, Iceland, Norway and Russia. In non-cooperative management like the present, all parties, except Norway, face the risk of being denied access to the resource when it is at a level where it does not migrate out of the Norwegian EEZ. Thus, we shall label these four parties Others, or simply O. The remaining party is then Norway, or simply N. Costs may differ between the parties due to different technology (different fleet characteristics) or different sailing distance to harvest the resource. The discount rate will differ to the extent that the time preference ratio differs. Based on the Beverton-Holt age-structured (cohort) model, the NPV of the fishery for a finite period for all parties exploiting the stock is given as:

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[34]   A harvest rule based on target fishing mortality is a simplification of the rule agreed upon by the parties in 2001, which also contained provisions for how fishing mortality should be reduced at low stock levels. Starting out with a stock, as assessed in 2003, the consequences of a target fishing mortality should be close to the consequences of the rule agreed upon in 2001.

$$NPV = \sum_{p,y,a} \{ (P_y(\bullet) - C_{p,y}(\bullet)) * Y_{p,y,a} * (1 + r_p)^{-y} \} \qquad (1)$$

where

$P_y(\bullet)$: average unit price of herring in year **y**

$C_{p,y}(\bullet)$: average unit cost of the fleet of party **p** of fishing herring in year **y**

$Y_{p,y,a}$: catch of the fleet of party **p** in numbers of age **a** in year **y**

$(1+r_p)^{-y}$: discount factor of party **p**

$Y_{p,y,a}$ is determined by equation (2):

$$Y_{p,y,a} = \frac{F_{p,y,a} N_{y,a} (1 - e^{-(F_{p,y,a} + M_{y,a})})}{F_{p,y,a} + M_{y,a}} * WC_{y,a} \qquad (2)$$

where

$F_{y,a}$: fishing mortality rate of age a in year y

$N_{y,a}$: number of fish of age a at the start of year y

$M_{y,a}$: natural mortality rate of age a in year y

$WC_{y,a}$: weight of fish (in catch) at age a in year y

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$N_{y,a}$ is determined by the recruitment function given in Essay 2. Norwegian spring spawning herring is characterised by stochastic recruitment, and the recruitment function used in this paper reflects this. Inserting (2) in (1) gives;

$$\text{NPV}= \sum_{p,y,a}\{(P_y(\bullet)-C_{p,y}(\bullet))*\frac{F_{p,y,a}N_{y,a}(1-e^{-(F_{p,y,a}+M_{y,a})})}{F_{p,y,a}+M_{y,a}}WC_{y,a}*(1+r_p)^{-y}\} \qquad (3)$$

The control variable will be a harvest rule in terms of a constant fishing mortality. Applied to a certain stock size, the fishing mortality will generate a TAC, which, in turn, will reduce the spawning stock of herring. The following year the spawning stock will give rise to recruits, the number of which depends on the level of the spawning stock as well as on stochastic factors. The new recruits will grow in individual size and suffer natural mortality. If the spawning stock has changed in size during the year, the application of a constant fishing mortality will imply a changed TAC the following year.

Under cooperative management, a harvest rule in terms of a constant fishing mortality will be set that maximises the value of equation (3). Each party will then achieve a payoff that corresponds to the economic value of their share of the TAC.

3.2   Critical minimum shares or threat points

In order for a cooperative solution to be self-enforcing, it must give N and O a payoff that is greater than the payoff each would receive from a non-cooperative solution. The non-cooperative solutions may therefore be considered as the boundaries for credible cooperative solutions, the critical minimum shares in a cooperative solution or simply the threat points in a bargaining solution.

Under non-cooperative management, it will be assumed that N, who defects, chooses a unilateral harvest rule that optimises its NPV, given that O maintains its share of the initial cooperative harvest rule. But once N's new harvest rule is common knowledge,

O will be assumed to choose a unilateral harvest rule that optimises its NPV, given that N maintains its new harvest rule. This response can be interpreted as a "punishment" for N, since it will increase the overall fishing mortality and consequently reduce the NPV of N's unilaterally chosen harvest rule. For an application of defecting and punishment in a cartel exploiting a non-renewable resource under capacity constraints, see Thomas (1991).

Going from cooperation to non-cooperation implies going from one common harvest rule to two unilateral harvest rules. When O's response, or harvest rule, is common knowledge, N will have an incentive to alter its harvest rule, and this process continues until one of the parties no longer finds it in its interest to alter its harvest rule. The game has then reached its non-cooperative equilibrium, and the payoffs to each party at this level will constitute their expected NPV of non-cooperation. In a trade-off between cooperation and non-cooperation, this payoff is then the critical minimum share that each party must receive to cooperate.

The time span until a non-cooperative equilibrium is established depends on how much time the two parties need to find out which harvest rule the other party has chosen. The process will start when one of the parties is not willing to honour a cooperative agreement. Assuming rational agents, as well as common knowledge of stock dynamics and the economics of exploitation, the defector's (here N's) unilateral harvest rule can easily be calculated by both parties. And the response from the other party, as well as all subsequent moves by the two parties, can be calculated before anybody has started to fish[35].

A central element forming these moves is the knowledge that at some biomass level the stock will switch from being straddling to becoming an exclusive Norwegian stock or vice versa. This level will occasionally be referred to as a "switching level". N and O will know that when the stock drops below the switching level, O's harvest will be zero, and both parties will take this into account when optimising their unilateral harvest rules.

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[35] Even though N is the first mover, it has no "first mover advantage" as assumed in Benchekroun and Van Long (2002). Immediately after N has made its move, O can make its move. By this procedure, the unilateral harvest rules that are consistent with the non-cooperative equilibrium solution will be effective from year zero.

In order to find its optimal unilateral harvest rule, N must optimise the following equation;

$$NPV_{(N)} = \sum_{y,a} \{(P_y(\bullet) - C_{N,y}(\bullet)) * \frac{F_{y,a}^N N_{y,a}(1 - e^{-(F_{y,a}^N + F_{y,a}^O + M_{y,a})})}{F_{y,a}^N + F_{y,a}^O + M_{y,a}} WC_{y,a} *(1+r_N)^{-y}\} \qquad (3')$$

Where;

$NPV_{(N)}$: Net present value of harvest to Norway

$F_{y,a}^N$: Control variable (fishing mortality exercised by N) to maximise $NPV_{(N)}$

$F_{y,a}^O$: Fishing mortality exercised by Other Parties, set to zero when spawning stock biomass <
Switching level [36]

Thereafter, O will evaluate whether its payoff will increase by replacing its share of the cooperative harvest rule with a unilateral harvest rule. This will be done by maximising (3'');

$$NPV_{(O)} = \sum_{y,a} \{(P_y(\bullet) - C_{O,y}(\bullet)) * \frac{F_{y,a}^O N_{y,a}(1 - e^{-(F_{y,a}^O + F_{y,a}^N + M_{y,a})})}{F_{y,a}^O + F_{y,a}^N + M_{y,a}} WC_{y,a} *(1+r_O)^{-y}\} \qquad (3'')$$

O will choose a harvest rule that maximises 3''. The control variable will be $F_{y,a}^O$, but the fact that $F_{y,a}^O$ automatically will be zero when SSB is below the switching level will be taken into account.

By varying the switching level, the moves and the payoff in the non-cooperative solution can be expected to change. We will now turn to an empirical assessment of the cooperative solution and the critical minimum shares or threat points.

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[36] The fishing mortality exercised by the other parties has an age-specific selectivity different from natural mortality. Adjusted for this, the fishing mortality exercised by O has the same effect for Norway as natural mortality.

4 Cooperative solution and critical minimum shares

With the exception of the (unknown) level when the stock starts to straddle (the switching level), all input data for the analysis are given in Essay 2 of this dissertation. In order to account for the effect the stochastic recruitment function will have for the results, the net present values of various harvest rules were simulated 1000 times, taking the expected values, or E(NPV). The forecast period was set to 50 years.

Fisheries on pelagic species, like herring, are often characterised by unit costs that do not increase as the biomass decreases, see Bjørndal (1987 and 1988). Whether these unit costs are constant, or equal to zero, does not have any other consequences for the cooperative solution and its critical minimum shares other than to adjust the E(NPV) of each party up or down. To simplify the analysis, harvest costs were set equal to zero for both parties. However, with such an assumption, the value of the harvest reflects the expected gross present value, E(GPV) of the catch. It will further be assumed that the price of the herring is constant and that the social rate of discount is equal to zero.

The implication of these assumptions, constant price, zero costs and discount rate is that we focus exclusively on the effect of the switching level of the stock[37]. Later, we will analyse how sensitive the solutions are to two of these assumptions.

4.1 Cooperative solution

When N and O cooperate on the management of the fish stock, both parties have full access to the EEZ of the other party, regardless of the level at which the stock

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[37] It should be noted that these assumptions may be relevant if various parties lack knowledge of harvest costs of each other's fleets.

becomes straddling. Figure 2 shows how the expected gross present value E(GPV) during a 50-year period, and the expected spawning stock biomass, E(SSB), at the end of the period develop as functions of harvest rules based on constant annual fishing mortality.
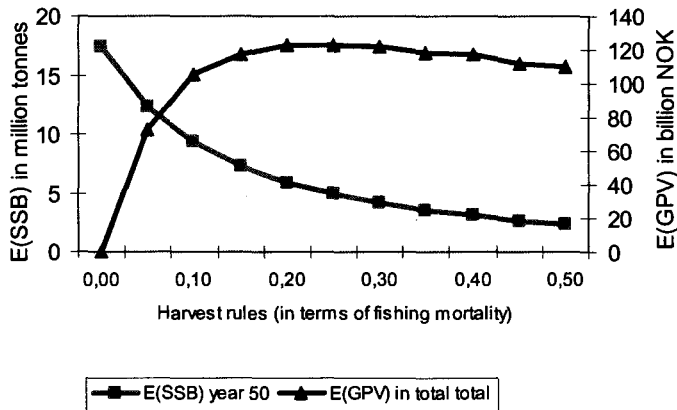

Figure 2: E(GPV) during a 50 year period and E(SSB) at the end of such a period as a function of various harvest rules. Prices constant at 2,500 NOK per tonnes and zero costs. Discount rate = 0%. Number of replicas set to 1000.

The E(GPV) reaches a maximum at a fishing mortality of approximately 0.20. This is equivalent to what Bjørndal *et al* (2004) found as optimal fishing mortality for a monopolist utilising this resource. The E(SSB) at the end of the period will then be 5.9 million tonnes, which is well above limit reference points for this stock (2.5 million tonnes)[38]. Further increases in the fishing mortality above 0.20 will reduce E(GPV) moderately, but E(SSB) substantially[39]. At F=0.20 the E(GPV) during a 50-year period is calculated to 123 billion NOK. With the existing allocation key

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[38]   The E(SSB) at the end of the period is approximately 10% lower than that found in Bjørndal *et al* (2004), but this may be due to different parameter values in the recruitment function. The curve showing E(GPV) is rather flat at fishing mortalities above 0.20. This is equivalent to what Bjørndal *et al* (2004) found the yield-curve to be at such fishing mortalities.
[39]   The figure further shows that little is gained by increasing the fishing mortality above 0.10. At such a fishing mortality, the expected SSB at the end of the period is 9.3 million tonnes, or close to 60% higher that the SSB resulting from a fishing mortality of 0.20.

between N and O, this gives N an E(GPV) of 70 billion NOK and O an E(GPV) of 53 billion NOK for the entire 50-year period.

4.2 Critical minimum shares for cooperation (threat points)

As mentioned, the threat points in cooperative sharing agreements can be found from the non-cooperative solution. To play out the non-cooperative game, the harvest generated by cooperative management is initially allocated 57% to N and 43% to O[40]. No capacity constraints for either party are assumed. Then, is there an incentive for N to defect from cooperation by fixing its own unilateral harvest rule, given that O sticks to its share of the agreed harvest rule? And, given that N deviates by increasing its unilateral harvest rule, will O have an incentive to do the same? As in the cooperative solution, it is assumed that the price is constant and that the costs and discount rate are equal to zero.

Table 1 shows the cooperative and non-cooperative solutions, assuming that the stock is straddling at all stock levels. For each solution the harvest rules (in terms of constant fishing mortalities), the E(GPV) and the E(SSB) are shown.

Table 1   *Cooperative and non-cooperative solutions when stock is straddling at all stock levels. Price constant at 2,500 NOK per tonnes and zero costs. Discount rate = 0%. F represents harvest rules (in terms of constant fishing mortality). E(GPV) is given in billion NOK, and E(SSB) in million tonnes. Simulation period is 50 years and number of replicas is set to 1000.*

	Cooperative solution		Non-cooperative solution	
	F	E(GPV)	F	E(GPV)
N	0.114	70	0.60	32
O	0.086	53	0.65	35
Sum	0.200	123	1.25	67
E(SSB)		5.9		0.4

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[40]   The parties used this allocation key during the period 1996-2002. Whether this, or a 50/50 allocation is used as the initial value in a non-cooperative game will not influence the boundaries for critical minimum shares.

Based on the assumptions given above, critical minimum shares implies that N gets at least 32 billion NOK (equivalent to 26% of a cooperative payoff of 123 billion NOK) while O gets at least 35 billion NOK (equivalent to 28% of a cooperative payoff of 123 billion NOK)[41].

Table 1 also shows the development of global fishing mortality and expected spawning stock biomass (SSB) as a consequence of going from cooperation to non-cooperation. In the non-cooperative solution, global F has increased to 1.25 and the SSB has stabilised at around 0.4 million tonnes. This is far below what is considered a minimum biological acceptable level for the stock (2.5 million tonnes). The non-cooperative solution for this two-party game is still found at a positive stock level, indicating that the stock will not become extinct. This is in contrasts to the result of Arnason *et al* (2001), who in a five-party competitive (non-cooperative) game found that the stock would go extinct. This difference may be due to the fact that the number of players in Arnason *et al* (2001) was more than twice the number in this study which is a factor that is known to be important for whether or not parties choose to cooperate, see Hannesson (1997).

In Table 1 the stock was assumed to be straddling at all levels. As mentioned previously, history has shown that the stock was confined within the EEZ of Norway in the 1970s and 1980s when the stock was at a low level. We do not however, know at which level this stock will become non-migratory in the future, since the migratory pattern is not solely determined by the size of the fish stock (ICES, 1995-2004). Still, it is of interest to consider the consequences of the stock's becoming non-migratory at a specific, positive stock level. We shall start with the case where the fish stock has an exclusive occurrence in the EEZ of Norway once the spawning stock biomass (SSB) is at or below 5 million tonnes (becomes straddling at stock levels above 5 million tonnes). Later, we will simulate how sensitive the threat points are to various switching levels. Table 2 shows the cooperative and non-cooperative solutions when the stock becomes straddling at 5 million tonnes.

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[41] With equal price, no harvesting costs and full access to the resource, these boundaries for a cooperative solution should be identical for the two parties.

Table 2 *Cooperative and non-cooperative solutions when stock becomes straddling at a level of 5 million tonnes. Other factors as in Table 1.*

	Cooperative solution		Non-cooperative solution	
	F	E(GPV)	F	E(GPV)
N	0.114	70	0.55	54
O	0.086	53	0.35	10
Sum	0.200	123	0.90	64
E(SSB)		5.9		0.9

When going from cooperation to non-cooperation, global F will increase to 0.90 and the E(SSB) will stabilise at 0.92 million tonnes. E(GPV) will be reduced for both parties, but especially for O since the stock with a high degree of probability will be within the EEZ of N. A stock level of 0.92 million tonnes is twice as high as the non-cooperative level found when the stock is straddling at all stock levels. However, it is still well below the minimum biologically acceptable level of 2.5 million tonnes.

Recall that each party optimises its E(GPV) as given by equation 3' and 3'' over a 50-year period. Even though the expected SSB in the non-cooperative solution is well below the switching level of 5 million tonnes, the E(GPV) of O will be positive due to two causes: First, there will be a "mining phase" on the stock, as illustrated by both Arnason *et al* (2001) and Bjørndal *et al* (2004). During the early years the stock will, with a high degree of probability, be above the switching level. Second, even though the expected SSB will be below the switching level towards the end of the period, the stochastic recruitment of the stock will generate a (small) probability that the stock will be above the switching level, at which O will harvest the stock with a fishing mortality of 0.35.

Intuitively, it is surprising that it should be rational for Norway to make moves that reduce the SSB so far below 5 million tonnes, but this result is caused by the stochastic nature of the recruitment process of this fish stock. If the stock becomes straddling at a stock level of 5 million tonnes, it will be necessary to reduce the stock well below that level to ensure that it, with a high degree of probability, is beneath a level where it starts to straddle.

The critical minimum shares, or threat points, for a cooperative agreement to be self-enforcing have been seen to change dramatically when the switching level is increased from zero to 5 million tonnes. At the latter level, the critical minimum shares for N and O are 44% and 8% respectively, whereas they were 26% and 28% respectively when the stock was assumed straddling at all stock levels. Figure 3 shows how critical minimum shares for N and O in a self-enforcing agreement develop as a function of the switching level.
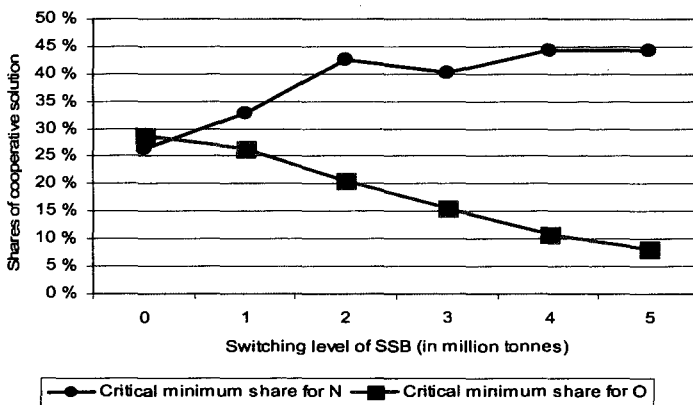
Figure 3   Critical minimum shares in a self-enforcing cooperative agreement at various levels, at which the stock becomes straddling. Constant price and discount rate assumed equal to zero.

The figure shows that the switching level is important for the critical minimum shares in a cooperative agreement. When this level is increasing, the critical minimum shares to N and O increase and decrease, respectively. At a switching level of 5 million tonnes and with the allocation key of 1996, the cooperative gain for O is substantial. The cooperative gain for Norway is also positive, but far less than for O.

This strengthens the results of Bjørndal et al (2004), who found that it would not be beneficial for one party to fish down the stock to a non-migratory level (assumed at 0.5 million tonnes).

5. Would an incentive-based allocation key be equal to the allocation agreed upon by the managers in 1996?

Within reasonable assumptions about the switching level, this paper finds huge cooperative gains in the management of the stock. If the harvest process among the various parties is not equally efficient, the cooperative benefits can be enhanced through side payments. Regardless of this, the challenge to the parties managing this stock is to agree on how to share the benefits of cooperation.

Practical experience for this herring stock has shown that the question of allocation has not been easy. The usual arguments in such conflicts have been based on "fairness" rather than incentives. Arguments of fairness have been how the stock is distributed between the various EEZs and the High Seas, dependence on the fishery as shown by historical catch data, and various parties' scientific efforts to assess the stock, see Engesæter (1993). As mentioned previously, in 1996 the parties agreed on a sharing of the TAC by which N got 57% and O 43%, but this agreement is no longer in effect.

However, when the stock is as vulnerable to overexploitation as this (schooling) herring stock is, there is evidently a need for sharing rules that to a greater extent are compatible with incentives among the players. Would such sharing rules give the 57% / 43% distribution or something different?

Two concepts, which to a greater extent are based on incentives, are the Shapley value (Shapley, 1953) and the Nash bargaining solution. Papers in which the Shapley value has been used are Lindroos (2004), Duarte *et al* (1999) and Pintassilogo and Duarte (2000). In a study of game-theoretic aspects of North Sea herring, Bjørndal and Lindroos (2004) use the Nash bargaining solution as a method when distributing cooperative benefits between the EU and Norway.

The virtue of the Shapley value is that its solutions reflect how various parties have contributed to the cooperative solution. A prerequisite for the solution is symmetric information regarding the payoff to all possible coalitions in a cooperative or non-

cooperative game. When this is common knowledge, the cooperative gains can be distributed according to how much the cooperative gains will be enhanced by each party.

The Nash bargaining solution distributes the cooperative gains equally to the parties of the game. In a game with only two players (as the one described in this paper), the Nash solution is identical to the Shapley solution. Keeping prices constant and costs as well as the social rate of discount equal to zero, Figure 4 shows how the Nash bargaining solution gives shares of the TAC to N and O.
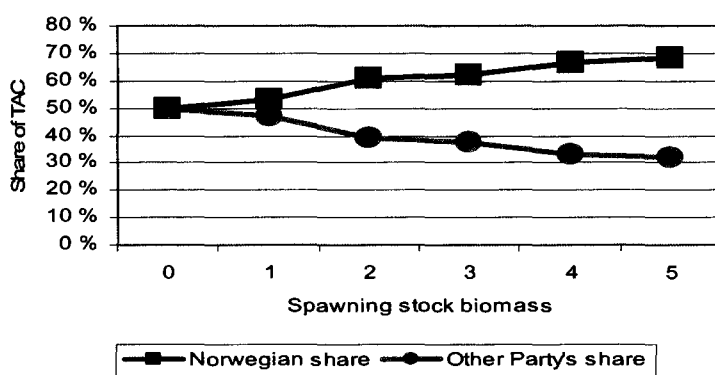
Figure 4: *The Nash bargaining solution for sharing a TAC of Norwegian spring spawning herring at various levels, at which the stock becomes straddling. Constant price and discount rate equal to zero.*

The Nash bargaining solution will give Norway a share of the TAC that ranges from 50% when the stock is straddling at all stock levels, to 68% if the stock has an exclusive occurrence in the Norwegian EEZ at stock levels below 5.0 million tonnes. The solution will, however, also be affected by assumptions made about discount rate and price formation, and we will investigate the importance of these two factors in the following section.

5.1   The sensitivity of the solution to price and discount rate

As mentioned, Munro (1979) has taught us that the bargaining powers of two parties who are to share cooperative benefits when exploiting a fish stock also depend upon their economics of exploitation and discount rate. When these differ between the parties, they will influence their bargaining power and hence their threat points as well as an incentive-based allocation key.

The sensitivity of our solutions to such differences will not be dealt with in the current paper. However, the analysis will address the question of how a price decreasing in harvest, and a positive discount rate, both of which apply equally to N and O, may affect the Nash bargaining solution. The alternative to a constant price will be an output elasticity of price of –0.29, based on estimated demand functions in Essay 2, and the alternative to a zero discount rate will be 10%.

Table 3 shows how these different assumptions affect the Nash bargaining solution. It is assumed that the switching level is 5.0 million tonnes. The Nash bargaining solution is not seen to be very sensitive to changing the assumption of constant price to an assumption of price decreasing in harvest.

Table 3   *Nash bargaining shares at various assumptions of price and social discount rate.*
            Switching level is set to 5 million tonnes.

Party	P_{const}, DR=0%	P_{dec}, DR=0%	P_{const},DR=10%	P_{dec}, DR=10%
N	68%	70%	76%	78%
O	32%	30%	24%	22%

Keeping prices constant and increasing the social rate of discount (to 10%) has a stronger effect on the Nash bargaining solution than going from constant prices to a price decreasing in harvest. When the discount rate is increased from 0 to 10%, the optimal cooperative (constant F) harvest rule increases from 0.20 to 0.40 and the expected spawning stock biomass at the end of the simulation period decreases from 5.9 to 3.0 million tonnes. Consequently, at such a discount rate and a switching level

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of 5 million tonnes, the fishery will to a much larger extent be conducted within the EEZ of Norway. This effectively reduces the critical minimum share of O, which will fall to approximately 1%, whereas it was calculated to 54% for N.

The results shown in Table 3 depend crucially on the switching level of the stock, set to 5 million tonnes. If the stock is straddling at all stock levels, a change of assumptions regarding price or discount rate would not move the Nash bargaining solution away from 50/50 as long as conditions regarding economics of exploitation and discount rate were equal to both parties. If the stock had a switching level between 0 and 5 million tonnes, the Nash bargaining solution would, depending on the assumptions made about price and discount rate, give N and O shares from 50% to the ones given in Table 3.

6.   Concluding remarks

Biological resources tend to increase their area of distribution as they grow. Fish stocks will often have a wider distribution at high stock sizes than at low, due to feeding migration. However, oceanographic conditions, as well as variations in food supply, imply that it is difficult to forecast the distribution of a fish stock. Norwegian spring spawning herring is a classical example of such a fish stock, and Atlantic Bluefin Tuna may be another (Bjørndal and Brasão, 2004). Their distribution is governed by their size, as well as by stochastic factors. When the stock studied in this paper is in a straddling state, it is vulnerable to exploitation by other nations than Norway.

In this paper we have analysed how various assumptions about the level at which a fish stock becomes straddling influence [i] the critical minimum shares for a cooperative agreement to be self-enforcing and [ii] the Nash bargaining solution. To the extent that the economics of harvesting will differ between the parties, this will influence both critical minimum shares and the Nash bargaining solution, but such differences were not dealt with in this paper.

It is found that the cooperative benefits are considerable. This result strengthens the conclusion drawn in Bjørndal *et al* (2004) where, under different assumptions about costs, it was found that it would not be optimal for Norway to fish down the stock to a level confined to the Norwegian EEZ. The "straddling level" assumed in Bjørndal (2004) was 0.5 million tonnes, and the current paper finds the conclusion to be valid also at much higher switching levels. Furthermore, the paper confirms general bioeconomic theory in that optimal stock level is reduced when the social rate of discount increases.

Both critical minimum shares and the Nash bargaining solution are highly sensitive to the level at which the fish stock becomes straddling. If this level increases, the critical minimum shares and the Nash bargaining share to Norway and Others will increase and decrease respectively. At constant prices and zero discount rate, the Nash bargaining shares to Norway and to Others increase from 50/50 to 68/32 when the level at which the stock becomes straddling increases from zero to 5 million tonnes. At a positive discount rate, the shares will be even more unbalanced. With constant prices and a discount rate of 10%, the Nash bargaining solution gives Norway a share of 76% and Others a share of 24%.

The results in this paper are based on an assumption that unilateral harvest rules in a non-cooperative solution could be expected to be set at a level that may imply stock collapse. Taking into account the increasing recognition of the need to manage fish stocks with a precautionary approach (United Nations, 1995) in general, and the earlier collapse of this stock in particular, such an assumption may be violated in practice. If one or both parties believe that the other party will not make moves that could imply stock collapse, this will influence both parties' critical minimum shares as well as the incentive-based allocation key.

The extent to which official adherence to the precautionary approach in fisheries management will affect "real world" moves in a non-cooperative exploitation of marine fish stocks is, however, highly uncertain. The non-cooperative exploitation of another major marine fish stock in the area (Blue Whiting) indicates that devotion to the precautionary approach has had limited effect on the moves made by the parties, see Heino (2004). On the other hand, the moves made by the relevant parties

exploiting Norwegian spring spawning herring since the allocation broke down in 2002 have, so far, not resulted in a fishery far in excess of the advised TAC. This may be an indication that the parties realise the penalties involved in broad defection from the joint harvest rule (as identified in this paper), which implies that the allocation of 1996 has strong self-enforcing elements. Nevertheless, it will not take more than one large move by one of the parties for an escalating exploitation to materialise.

Since the seminar article by Munro (1979), it has been known that differences in the economics of exploitation of a fish stock between two parties influence their bargaining position when sharing the benefits of cooperative management. This paper has shown the importance of recognising dynamics of straddling stock's distribution when analysing critical shares for self-enforcing cooperative agreements as well as incentive based allocation keys. The effect, that recognition of the precautionary approach may have on credible moves in such games is a topic for future research.

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Results, concluding remarks and future research

Results

Starting out from the pioneering work of Warming (1911, 1931) and Gordon (1954), the literature on fisheries economics has covered many aspects of how to optimise the economic value from these resources. The aim of this dissertation has been to analyse empirical aspects of relevance for harvest rules or investment decisions for fish stocks where [i)] the investment decision for the stock often is taken by the state(s) whereas investment decisions in harvesting capital are made by the industry, and [ii)] the investment decision must be made jointly with other nations, which necessitates a fair sharing of the stock. The dissertation consists of three essays, whose main conclusions are the following:

Essay 1:   Variable unit costs in output- regulated fisheries

The essay estimates both the output elasticity and the stock elasticity of variable unit costs for three Norwegian vessel groups fishing Norwegian spring spawning herring and five Norwegian vessel groups fishing Northeast Arctic Cod.

Variable unit costs with respect to output

For both fisheries, the output elasticity of variable unit costs is found to be negative and significantly below zero. This implies that variable unit costs decrease as output/IVQs increase, which reflects the existence of set-up costs prior to each fishing expedition and that the number of expeditions increases at a slower rate than increases in output or IVQ. Figure 1 shows the estimated relationship between variable unit costs and IVQ for the three vessel groups fishing Norwegian spring spawning herring.
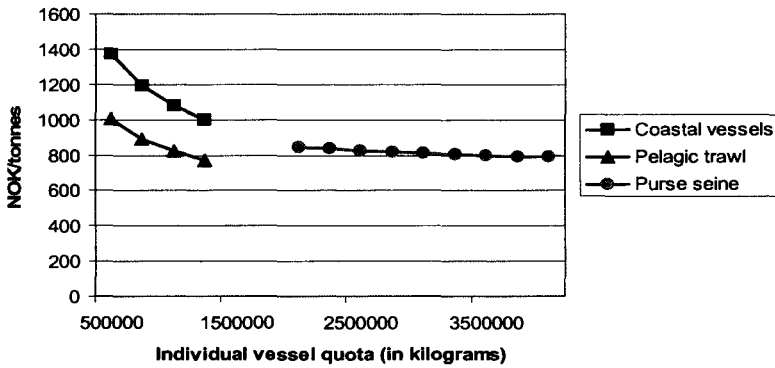
Figure 1   *Estimated variable unit costs as a function of individual vessel*
                 quotas (IVQ) for three Norwegian fleets fishing Norwegian
                 spring spawning herring.

It can easily be seen that for two fleets, the coastal vessels and the pelagic trawlers, variable unit costs fall substantially as IVQs increase, whereas the variable unit costs of the purse seiners are far less sensitive to changes in the IVQ. Figure 2 shows the corresponding relationship between variable unit costs and IVQ for five Norwegian fleets fishing Northeast Arctic cod.
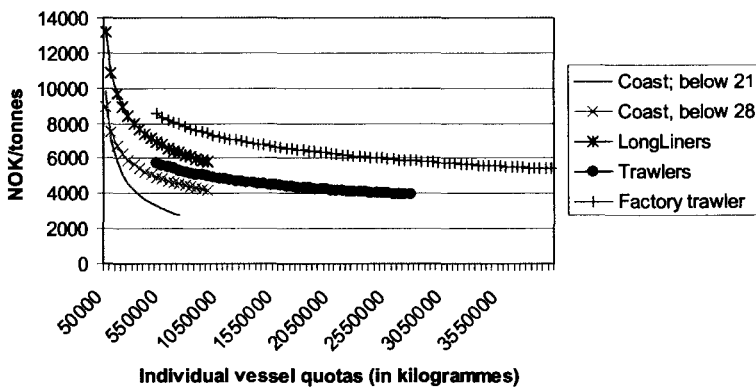
Figure 2   *Estimated variable unit costs as a function of individual vessel*
                 quotas for five Norwegian fleets fishing Northeast Arctic Cod.

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Variable unit costs for all vessel groups fishing cod fall when IVQs increase, but more so for the coastal vessels and the long-liners than for the trawlers. The essay discusses possible explanations, and find that these may imply high-grading at low IVQ levels.

Variable unit costs with respect to stock

Three vessel groups participate in the herring fishery and five groups in the cod fishery. When variable unit costs are defined as the sum of operating and quasi-fixed costs, a significantly negative stock elasticity of variable unit costs is found for two of the vessel groups harvesting herring and for all five vessel groups harvesting cod. When variable costs were restricted to operating costs, the stock elasticity of operating unit costs was no longer significant for two of the three fleets fishing herring, but still significant for three of the five vessel groups fishing cod. Figure 3 show the estimated relationship between variable unit costs and IVQ for the various fleets fishing Norwegian spring spawning herring.
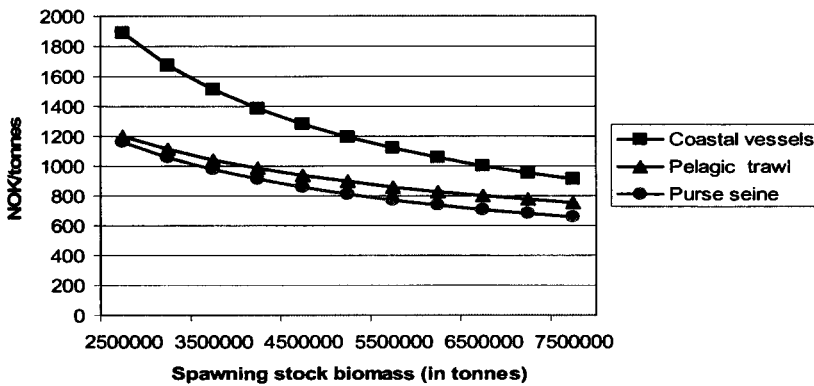

Figure 3   *Variable unit costs as a function of spawning stock biomass for three Norwegian fleets fishing Norwegian spring spawning herring.*

Variable unit costs for the coastal vessels fishing Norwegian spring spawning herring are more responsive to changes in the spawning stock than the variable unit costs for the two other vessel groups. Figure 4 and 5 show the corresponding relationship for fleets harvesting Northeast Arctic cod.
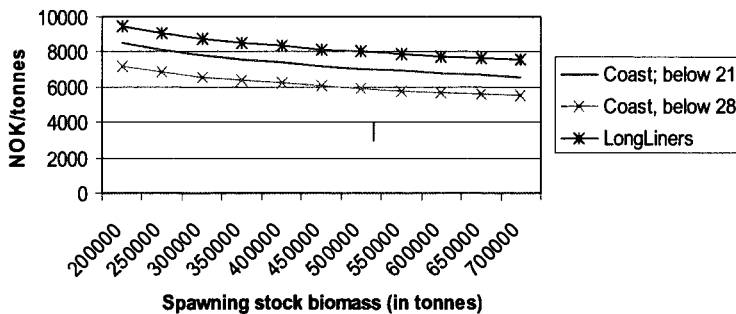
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Figure 4   *Variable unit costs as a function of spawning stock biomass for coastal vessels and long liners fishing Northeast Arctic Cod.*

Variable unit costs for the coastal vessels fishing Northeast Arctic cod are responsive to changes in the spawning stock, but as can be seen, there is no one-to-one relationship indicating that these costs drop proportionally with increases in stock size.
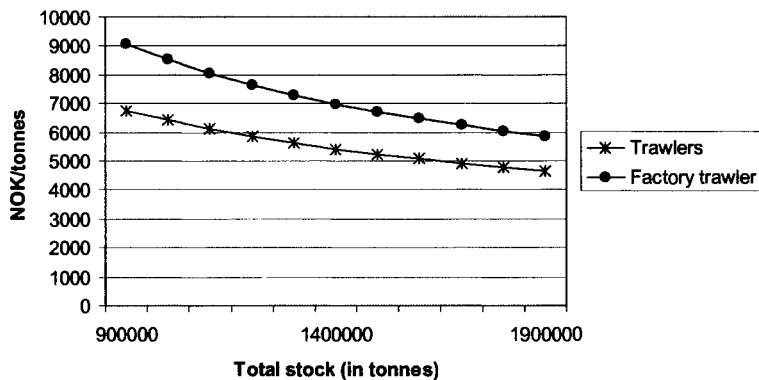

Figure 5   *Variable unit costs as a function of total stock biomass for two groups of trawlers fishing Northeast Arctic Cod.*

For the trawlers, variable unit costs seem more responsive to changes in the stock than is the case for the coastal vessels and long-liners.

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The general picture is that variable unit costs decrease as output and fish stock increase. These results should be taken into account when identifying the optimal harvest rule for the fish stocks concerned. While unit costs that decrease in stock will increase the target stock level, unit costs that decrease in output may move the target stock level in the opposite direction. Contrasted with assumptions of stock elasticities close to 1 and no relationship between output and unit costs, the findings will reduce target stock level. In addition to this, the findings have several other policy implications:

First, since variable unit costs and their responsiveness to output and fish stock differ between fleets (harvesting the same fish stock), what can be considered an optimal management of the stock will differ between vessel groups. In order to find the policy that optimises the net economic revenue to the fleets combined, each fleet's significance must be weighted according to its expected share of the harvest.

Second, to the extent that operating profit per unit harvest differs between the fleets, quota allocation may be an important instrument to enhance overall profitability. To evaluate how overall profitability will respond to alternative quota allocations, there is a need for a bioeconomic simulation model. Such a model should also takes account of possible differences in which price the fleets obtain for their harvest as well as the various fleets exploitation pattern in the fishery.

Third, the negative output elasticities of variable unit costs found in the cod fisheries raise some concerns. If these reflect high grading at low output levels, managers should be concerned about the implementation success of an output regulation when output from the industry is (forced) down. One policy implication is that monitoring and control should be increased when output from the industry is reduced. Another policy implication would be to reduce the number of vessels allowed to participate in a fishery to keep output at firm-level stable when output of the industry is reduced.

Fourth, the relatively low stock elasticity of variable unit costs in the cod fisheries is also cause for concern. Departing from an assumption of stock elasticity of output at around 1, it has often been assumed that the cod fishery does not threaten demersal

fish stocks. The reasoning is well known: as stocks decline, catch per unit effort decreases and variable costs per unit catch increase up to a point when fishing is no longer profitable, at which level fishing ceases and the stock can rebuild. The low stock elasticity found in this paper indicates that variable unit costs are only moderately sensitive to stock size, which in turn indicates that a fishery will be profitable at far lower stock levels than what they would be at stock elasticities around 1.

Essay 2:   Harvest rules when price depends on quantity

The essay makes use of a fleet and age-structured bioeconomic model to analyse performance of harvest rules (stock investments) for the Norwegian fleets fishing Norwegian spring spawning herring. In particular, a target escapement strategy (with a most rapid approach) is contrasted with a rule characterised by target fishing mortality.

The recruitment process of Norwegian spring spawning herring is highly variable. This implies that a target escapement policy with a most rapid approach towards the target will produce highly variable catch quotas. There would be a moratorium when the assessed stock is below the target level and otherwise a quota level reflecting the distance between the assessed stock and the target level. The rule established by the managers of the stock, which is characterised by target fishing mortality, implies a much lower variability in catch quota from year to year.

If prices could be assumed to be constant in harvest, Reed's conclusion is empirically confirmed for this stock. A target escapement strategy with the most rapid approach gives a higher net present value of the catch than the existing harvest rule applied by the managers of the stock. It should be noted, however, that this result does not include potential higher adjustment costs due to lack of alternative use for several factor inputs.

When prices fall in harvest, the target escapement strategy with the most rapid approach gives a lower expected net present value of the catch than the existing

(target fishing mortality) rule applied by the managers. An additional benefit of the rule applied by the managers is expected lower (but here non-quantified) adjustment costs in the industry than the target escapement policy.

Due to the stochastic recruitment function, there is always a chance that the stock may drop below what can be considered "safe biological limits", which for this stock is calculated by ICES to be 2.5 million tonnes. It should be noted that when this happened in the late 1960s, it took nearly two decades until the stock recovered to above the critical level.

This essay therefore also compares the performance of two rules when the stock is in need of recovery. Mean catch, expected net present value of catch, expected spawning stock biomass (SSB) at the end of the simulation period, and the probability that the stock would be below minimum biological level during the simulation period served as performance indicators. It was found that target escapement is superior to the rule applied by the managers if stock recovery is the only objective, but that the rule chosen by the managers is superior if the only objective is to maximise the net present value of the catch. To a fishery manager, usually concerned with both, there is thus a need for a trade-off between the two objectives when deriving the recovery strategy.

When identifying an optimal harvest rule for this stock, these results have several policy implications.

First, when price depends on quantity, a rule characterised by target escapement and a most rapid approach involves large penalties. This was theoretically shown by Clark and Munro (1975), and is empirically verified for Norwegian spring spawning herring in this essay.

Second, when the stock of Norwegian spring spawning herring is within safe biological limits, the rule established by the managers of this fish stock has a better performance than a target escapement rule with a most rapid approach.

Third, in a period when the stock is in need of recovery, a target escapement with a most rapid approach implies faster recovery than the rule established by the managers.

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On the other hand, the rule established by the managers implies fishing even at low stock levels. This presents the managers with a trade-off between the desired pace of recovery and economic return from the fishery.

Essay 3: A small pie for me or a big one to be shared?

Being confined within the Norwegian EEZ at low stock levels, Norwegian spring spawning herring started to straddle when its size increased. For Norway, who hosted the stock at a low stock level, this raises the question of whether it is better economics to exploit the stock at a level where it is kept within the Norwegian EEZ or to let it grow and share it with other countries.

Simulating with various levels at which this stock switches from being confined within the Norwegian EEZ to straddling, the essay analyses cooperative benefits, critical minimum shares (threat points) and the Nash cooperative bargaining solution.

Substantial cooperative benefits were found for this stock. It was found that the critical minimum shares for cooperation, as well as the Nash bargaining solution, depended on the level at which the stock starts to straddle (the switching level). For two parties, where the economics of harvesting were identical and the stock was assumed to be accessible to both parties at all stock levels, the Nash bargaining solution gave 50/50 shares. However, if the switching level occurred at a positive/higher stock level, the party that hosts the stock in its non-migratory state (Norway), increases both its critical minimum share as well as its Nash bargaining solution. Figure 6 shows how the Nash bargaining solution was found to develop as a function of switching level for the stock.
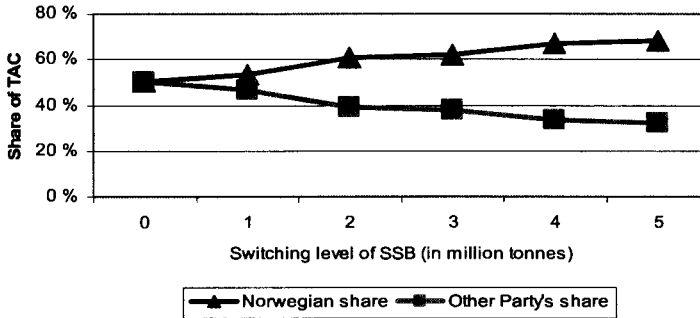
Figure 6   *Nash bargaining solution as a function of the level at which*
                 Norwegian spring spawning herring becomes straddling. Constant price and
                 discount rate equal to zero.

The policy implications of the essay are the following.

First, the cooperative benefits of this stock are substantial. This has previously been shown by Bjørndal *et al* (2004) and is confirmed by this essay. These benefits imply that, for a wide range of allocation keys, a cooperative management of the stock will have strong self-enforcing elements.

Second, the level, at which the stock switches from being a straddling stock to an exclusive Norwegian stock, has implication for both critical minimum shares as well as Nash bargaining shares. While this level cannot be known up-front, the parties exploiting the stock may have beliefs about the switching level. The essay then shows the critical minimum shares as well as the Nash bargaining shares that correspond to these beliefs.

Concluding remarks and future research

As mentioned above, the exploitation of fish stocks in the Northeast Atlantic is characterised by a dichotomy of decision-making. The state will make decisions regarding harvest rule (investment policy) for the fish stock whereas the industry will make investment decisions regarding physical capital and how to utilise various production factors when exploiting a fish stock.

When deriving optimal harvest rules, the state should assess and take into account how various harvest rules may influence decision-making of the industry. During the last 50 years, the fisheries economic literature has provided several theoretical results that are highly relevant for this issue. For the fish stocks of interest, there is a need for empirical research to assess the importance of these theoretical results.

This dissertation provides some of this empirical research for two of the most important fish stocks for Norwegian fishermen, namely how variable unit costs are affected by stock and output, whether target escapement (with a most rapid approach) is the optimal rule when price decreases in harvest, and finally the significance of the straddling nature of a fish stock for Nash bargaining shares.

To implement economic aspects of relevance for harvest rules, there is a general need for more empirical research, focusing on the following.

Output elasticity of price

An important area for future empirical research is assessment of the output elasticity of price or how the price obtained for fish from various fish stocks changes as output changes. As shown in essay 2, whether price changes as output changes has fundamental bearings for the choice of harvest rule. Thus, this empirical relationship should be established for more fish stocks.

Output and stock elasticity of variable unit costs

Another important area for future research is assessment of variable unit costs for more fisheries. Essay 1 provides such results for two Norwegian fisheries, but it

would be of interest to assess variable unit costs in other fisheries. This could either be other fleets exploiting the same stocks, or other fleets exploiting other fish stocks. Such knowledge has implication for the harvest rule chosen.

Investment behaviour in the fishing industry
An issue not analysed in this dissertation is the investment behaviour of the fishing industry. To the extent that various harvest rules influence investment decisions in the fishing industry, and thus the long-term fixed costs, this influence will have relevance for the choice of harvest rule, and should be explored further.

Bioeconomic simulation models
To incorporate the knowledge on how price, variable unit costs and investment decisions depend on harvest rules, there is a need for empirical research directed towards building bioeconomic simulation models. For the models to gain credibility among the decision-makers, it is important that they also incorporate important biological features for the relevant fish stocks.

Incentive-based sharing keys for shared fish stocks
As shown in essay 3, the benefits of cooperative management of Norwegian spring spawning herring are substantial. It may however be hard for the parties exploiting a fish stock to agree on sharing keys. This emphasizes the need for further research on sharing keys.