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Harvest rules when price depends on quantity The case of Norwegian spring spawning herring (*Clupea Harengus L.)*

by

Per Sandberg

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INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION

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Abstract

For fish stocks where the unit price of harvest is constant, unit harvest costs independent of quantity and non-increasing in biomass, regulation based on target escapement has been shown to optimise the net present value of harvest to society. Such a policy will result in a bang-bang regulation with closure of the fishery once the fish stock drops below the target and vice versa. The optimality of the target escapement policy has, under the same economic conditions, also been shown to hold for fish stocks characterised by stochastic recruitment. In this paper, the optimality of a target escapement policy for a fish stock with stochastic recruitment, but unit price of harvest decreasing in quantity, is empirically investigated, in the case of the Norwegian fishery on Norwegian spring spawning herring. For this fishery, it is found that a target escapement policy is no longer optimal.

1. Introduction

Regulating catch levels by harvest rules are widely used management tools in fisheries. Clark (1976) showed that a target escapement 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 rules only setting the conditions for closure of a fishery[1].

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 does assume fish prices constant in catch level and unit harvest costs independent of biomass. Interestingly, 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, which may be hard to implement in practice[2].

The assumption of constant fish prices or, in other words, an infinitely elastic demand is crucial to both Clark and Reed's outcome. In fact, Reed acknowledges that the optimality of a target escapement rule may be violated if this assumption does not hold. Somewhat surprisingly, the fisheries research community has not carried through with research to relax the assumption of price constant in catch levels. The purpose of this paper is to focus research attention again on this important area. The contribution of this research is to empirically investigate the importance of the constant price assumption on the optimality of a target escapement rule. 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 comparison is done by the use of a bioeconomic model. Data used in measurement and testing are from the Norwegian fishery on Norwegian spring spawning herring (*Clupea Harengus L.*), the largest pelagic fish stock in the Northeast Atlantic. This fish stock is characterised by stochastic recruitment and price decreasing in harvest level.

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[1] This bang-bang regulatory approach has been applied to the North Sea herring fishery by Bjørndal (1987 and 1988).

[2] Both Clark (1976) and Reed (1979) assume implementation of a "bang-bang" regulatory policy is costless. 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.

The paper is organised as follows: In section 2, the fish stock and the fishery is described. In section 3 the bio-economic model is presented. Results are provided in section 4 whereas conclusions are drawn in section 5.

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.

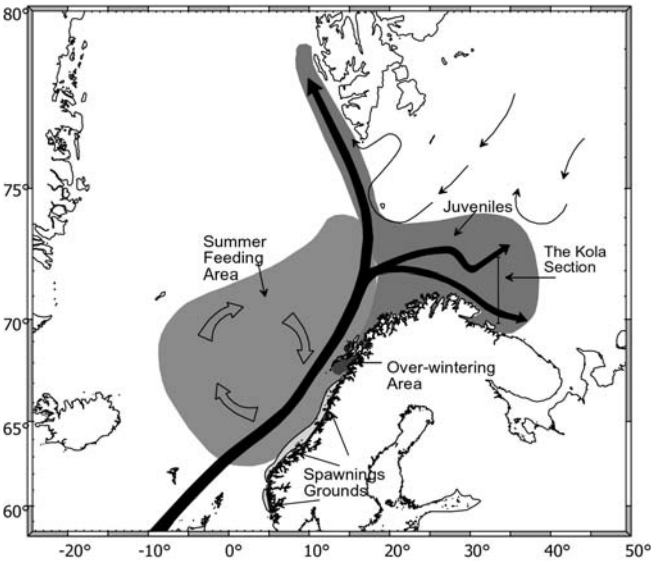

Figure 1. Migration pattern for Norwegian spring spawning herring. The coloured area shows the current distribution of herring, whereas the black arrows show inflow of warm Atlantic water (the Gulf Stream).

The size of the spawning stock biomass (SSB) of Norwegian spring spawning herring varies considerably. The International Council for the Exploration of the Seas (ICES) has estimated the SSB in 1950 to 12.7 million tonnes, whereas it collapsed down 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.

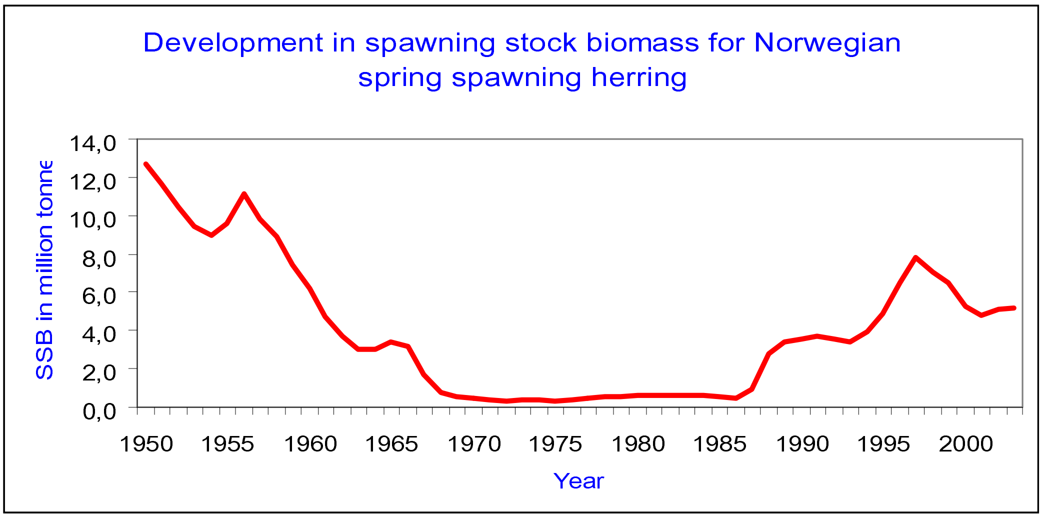

Figure 2 *Spawning stock biomass of Norwegian spring spawning herring 1950 – 2003. Source: ICES, 2003a.*

Figure 2 shows a stock with great fluctuations. In Toresen and Østvedt (2000) the conclusion is drawn that these fluctuations are caused by variations in the survival of recruits, which again 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 *et al* (1980) provides 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[3].

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.

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[3] Since 2003, the question of allocation has been reopened. Currently, there is no agreement on how to share the TAC.

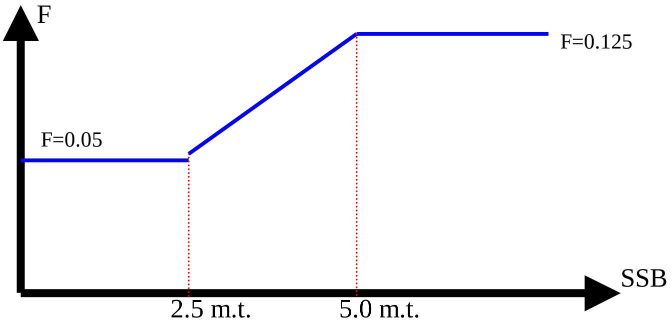

Figure 3 *Graphical presentation of a harvest rule where the fishing mortality (F) is fixed at 0.125 when the assessed SSB is above 5.0 m.t., linearly decreasing to 0.05 when the assessed SSB reaches the level 2.5 m.t. and fixed to 0.05 when the SSB is below that level (2.5 m.t.).*

Prior to adoption of the rule, its performance was evaluated by the use of medium-term simulations (Bogstad *et al*, 2000). 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). The expected net present value of the rule was, however, not calculated nor was the rule compared with a target escapement rule. However, 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 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 find 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 has been discussed in several papers, see Sandal and Steinshamn (1997 and 2001). For a more thorough discussion of the 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 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; the coastal vessels, the purse seiners and the pelagic trawlers. What distinguishes the fleets are size of the vessels, range of operation, and to some extent gear. These technological differences imply that both revenue and costs vary substantially between the fleets (Norwegian Directorate of Fisheries, annual reports) and Sandberg (2004)).

- 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 like 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.

Norway has, for several years, been allocated 57% of the TAC. The distribution of the Norwegian quota on 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[4].

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), which are established annually by the management authorities. The Directorate of Fisheries registers prices of the individual landings.

Within each fleet segment, the vessels are regulated with individual vessel quotas. Faced with such an output control, a profit-maximising behaviour of 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 Sandberg (2004) and will be used in this paper. These unit costs are non-increasing in both catch and biomass.

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 *et al* (2001) use an aggregated growth function when assessing game theoretic aspects related to the stock[5]. Lindroos (2000) and Bjørndal *et al* (2004) both use disaggregated cohort models in their analysis of other game theoretic aspects of the same stock.

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[4] For an introduction to some main elements of the fishery management of Norway, see Årland and Bjørndal (2002).

[5] When estimating the parameters in the growth function for Norwegian spring spawning herring, Arnason *et al* (2001) does however, not find them to be statistical valid.

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. To take care of the stochastic recruitment process, this paper relies on a disaggregated cohort model, outlined in Appendix A.

The criterion, 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:

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

where

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

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

$Y_{f,y}$: catch / quota for fleet $_{\mathbf{f}}$ in year $_{\mathbf{y}}$

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

The catch, or quota, per fleet is each year determined by the harvest rule, the dynamics of the fish stock as well as 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. Inserting equation (A5) and (A7) from Appendix A, the expected NPV for the Norwegian catch of Norwegian spring spawning herring can be written as;

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

where

$N_{y,0}$: R_y

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

$M_{y,a}$: natural mortality of cohort $_{\mathbf{a}}$ in year $_{\mathbf{y}}$

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 separates 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. One would therefore assume that the catch taken by purse seiners can 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 elasticity of price with respect to harvest was to - 0.29, - 0.31 and - 0.34 for the three vessel groups. These elasticities were not statistically different between the vessel groups, but 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 existing fleets.

Fishing mortality (F) 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 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.

Biological and fishery data are given in Appendix B, whereas economic data are given in Appendix 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, 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.

4. Results

The E[NPV] of target escapement (TE) levels from 1 to 7 million tonnes were evaluated and contrasted with the E[NPV] of the ad-hoc rule[6]. 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.

4.1 Constant prices

The level of constant prices was set to the average real price for each fleet during the period 1990-2000 (see Appendix C, Table C3). Table 1 shows the E[NPV] of each rule over a 50-year period.

Table 1. The expected NPV, E[NPV] in million NOK of the Norwegian harvest of Norwegian spring spawning herring in 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 is set to 5%. 1000 replicates. Biological and economic parameters as given in Appendix B and C respectively, with stock in numbers as in 2003.

Target escapement (in million tonnes)	E[NPV] Infinitely elastic demand
1	8 707
2	**9 264**
3	9 102
4	8 826
5	7 952
6	6 428
7	5 478
Ad hoc rule	**6 048**

Table 1 shows that when prices are constant, E[NPV] is considerably higher 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. Thus, when prices are fixed (demand is infinitely elastic), Reeds conclusion regarding the optimality of target escapement rules is not challenged by our empirical investigation of the Norwegian fishery on Norwegian spring spawning herring.

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: Concerning Norwegian spring

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[6] 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.

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 *et al* (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.

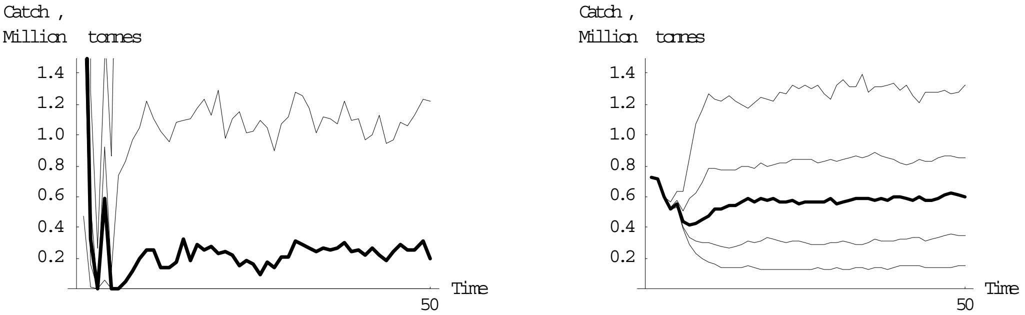

Figure 4 Stochastic forecasts of 500 replicates of harvest per year in a 50-year period. The bold line represents the median, while the thin lines represent the 25 and 5% percentiles above and below the median. The left panel represents the catch forecasts of a target escapement rule at a target level 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 stresses 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 fall. This is caused by the average prices in the rules that are severely reduced by the harvest levels[7]. Table 2 shows the expected E[NPV] of target escapement rules (with various targets) and the ad hoc harvest rule established by the managers of the stock, when prices decrease in harvest.

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[7] An additional explanation for the reduced level of E[NPV] in Table 2 relative to Table 1 is the high fixed prices applied in section 4.1.

Table 2. The expected NPV (in million NOK) of the Norwegian harvest of Norwegian spring spawning herring in 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. Biological and economic parameters as in Appendix B and C respectively, with stock in numbers as in 2003.

Target escapement (in million tonnes)	E[NPV] Prices decreasing in harvest
1	1 296
2	1 631
3	1 873
4	2 057
5	**2 072**
6	1 739
7	1 608
Ad hoc rule	**3 265**

At price elasticities found in Appendix C, the optimality of a target escapement rule is challenged by the ad hoc rule established by the managers. For the elasticity of price with respect to quantity 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 fixed, 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[8], it mitigates against the adverse effect, which the bang-bang regulation has on prices.

4.3 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 its assessed level in 2003 of approximately 5 million tonnes. With such a starting point, the specified stock dynamics and harvest rules 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 recover. In such a depleted stock environment, managers will also have obligations to manage the resource in accordance with 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 obligations to

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[8] 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.

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 decreasing in catches. Table 3 shows the performance of each harvest rule in relation to three indicators.

Table 3 *Mean catch, expected NPV amd 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. Biological parameters as in Appendix B, with stock in number as in 1975. Economic parameters as in Appendix C, with prices decreasing in catches. Target escapement set to 5 million tonnes.*

Harvest rule	**1** Mean Catch	**2** E[NPV]	**3** E[SSB]	**4** P(SSB<2.5 m.t.)
Target escapement	0.26	326	4.3	56 %
Ad hoc rule	0.22	869	4.2	70 %

In a depleted stock environment, column 1 in 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[9].

Column 2 in 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. Column 4 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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[9] This result is caused by the prices decreasing in harvest. Keeping prices fixed, 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).

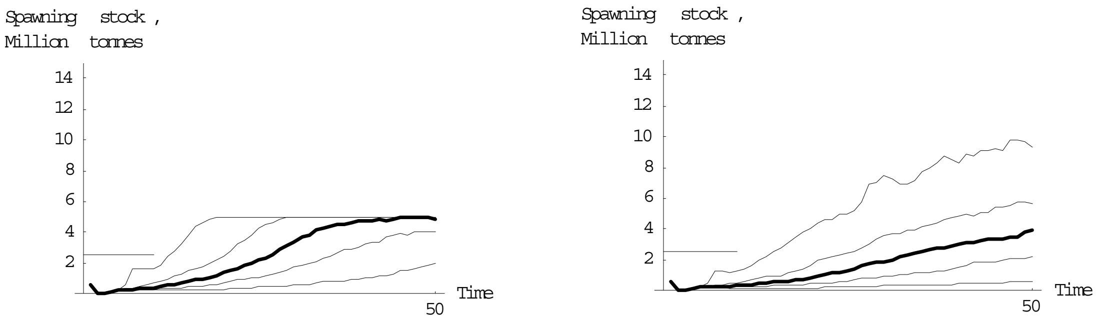

Figure 5 Stochastic forecasts of 500 replicates of harvest per year in a 50-year period when starting simulations with the stock size as in 1975. The left panel represents target escapement with target level 5 million tonnes. The right panel represents the ad-hoc rule established by the managers.

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.

5. Concluding remarks

The purpose of this paper has been, to investigate empirically the importance of the constant price assumption on the optimality of a target escapement rule. For the fishery analysed, it is found that when the constant price assumption is relaxed, target escapement can no longer claim optimality. 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 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 growth rate of the stock on the one hand and the discount rate of the society on the other. If the growth rate of 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 growth rate of the stock equals the discount rate of society.

When the assumption of fixed prices, or infinitely elastic demand, is relaxed, a market effect becomes relevant when deciding upon harvest rule. Taking account of this, 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 what a target escapement would imply.

As already touched upon in the introduction, there is another reason for not using target escapement rules in practical fishery management. These are the substantial adjustment costs, which the bang-bang consequences of a target escapement policy would imply. These costs have not been analysed in the present paper, but should be of interest to explore 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 elasticities of demand used in this paper. Another harvest rule, which consequences would be of interest to evaluate, would be a target escapement strategy where the annual TAC were not allowed to exceed specific levels.

Acknowledgements

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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 motality ***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:

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

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).

$$Y_y = \sum_a C_{y,a} WC_{y,a} \tag{A7}$$

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.

B1 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)

B2 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)

B.3 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

C1 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%

C2 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 inelastic to price changes[10]. 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.

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[11]. 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[12]. Several specifications of the relationship were tested, both linear and log-linear. The following however, was found to give highest explanatory power:

$$P_{f,y} = \alpha Y1_{f,y}^{\beta_1} Y2_{f,y}^{\beta_2} e_f^{\varepsilon} \qquad \text{(C1)}$$

where

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

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[10] 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.

[11] 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.

[12] 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.

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

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

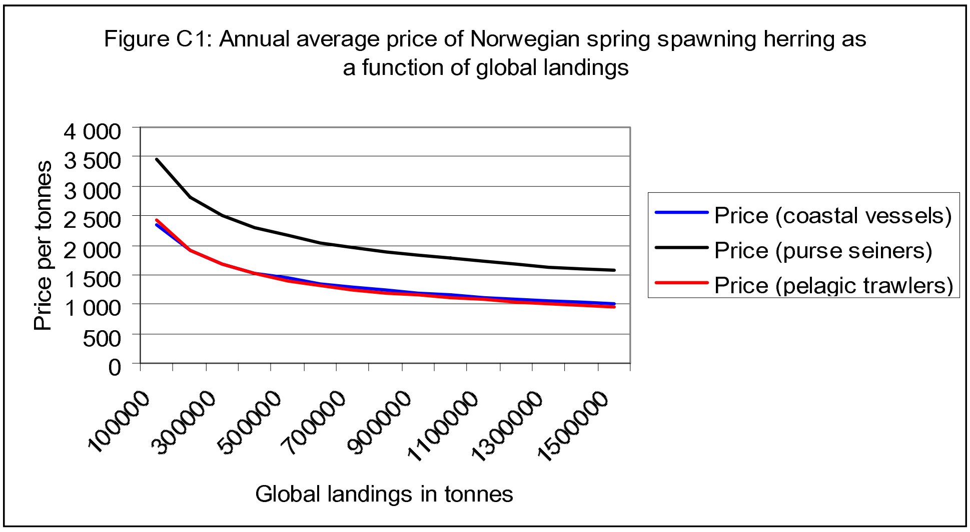
e_f : random error, assumed lognormally distributed with zero mean

Table C2 gives the estimated parameters of equation B1

Table C2 *Parameters estimated for the price function C1. Ssignificance 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.



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.

C3 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 are in the range 300 – 500,000 tonnes.

Table C3 Real average prices per fleet during the period 1990-2000, NOK/tonnes.

Fleet	
Coastal	1.655
Purse seine	2.221
Pelagic trawl	1.468