Marine Resource Economics, Volume 18, pp. 263–274
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0738-1360/00 $3.00 + .00

Harvesting Strategies in a Fish Stock Dominated by Low-frequency Variability: The Norwegian Spring-spawning Herring (*Clupea harengus*)

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Abstract *Heavy positively autocorrelated natural fluctuations in a fisheries stock level are problematic for fisheries management, and collapses in the stock dynamics are difficult to avoid. In this paper, we compare three different harvesting strategies (proportional harvesting, threshold harvesting, and proportional threshold harvesting) in an autocorrelated and heavily fluctuating fishery — the Norwegian spring-spawning herring (Clupea harengus) — in terms of risk of quasi-extinction, average annual yield, and coefficient of variation of the yield. Contrary to general expectations, we found that the three strategies produce comparable yields and risks of quasi-extinction. The only observable difference was slightly higher yield and variation in the proportional threshold strategy when the yield is optimized. Thus, it remains an open question as how to characterize the circumstances when it is particularly needful to apply threshold levels in harvest policies.*

Key words Harvesting, Norwegian spring-spawning herring, population variability, risk, maximum sustainable yield.

JEL Classification Code Q22.

Introduction

The decline of marine resources is common knowledge among fisheries scientists as well as wider audience (Ludwig, Hilborn, and Walters 1993; Hutchings 2000). It has

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We thank Trond Bjørndal for helpful comments on an earlier draft and Mike Fowler for improving the English. We also thank two anonymous reviewers for critical comments. This study was supported by the Academy of Finland to Veijo Kaitala in the Centre of Excellence in Evolutionary Ecology at the Department of Biological and Environmental Science at the University of Jyväskylä. Niclas Jonzén is grateful for financial support from the Spatial Ecology Program at the Department of Ecology and Systematics, University of Helsinki, and the Swedish Foundation for International Cooperation in Research and Higher Education. Veijo Kaitala acknowledges support by the European Community—Access to Research Infrastructure action of the Improving Human Potential Programme.

been argued that fisheries economics is in crisis, as it seems to be helpless in light of this history. Thus, the development, or rather the decline of marine resources, may call for new approaches to their management (Pitcher, Hart, and Pauly 1998) and other "wicked problems" lacking in definitive formulation and tests for solutions (Ludwig, Mangel, and Haddad 2002). Optimal resource management has been studied in deterministic and stochastic settings using a variety of objective functions that may contain various biological and economic considerations (*e.g.*, Mangel 1985; Clark 1976). Others have approached the problem from a slightly different angle and have compared alternative harvesting strategies in terms of biological risk (*e.g.*, Lande, Engen, and Sæther 1994; 1995; Lande, Sæther, and Engen 1997)—emphasizing that fish stocks may indeed collapse when heavily exploited—rather than trying to find the optimal feedback control policy maximizing an objective function over a finite time horizon.

In a number of papers (Lande, Engen, and Sæther 1994, 1995; Saether, Engen, and Lande 1996; Engen, Lande, and Sæther 1997; Lande, Sæther, and Engen 1997; Ludwig 1998), it has been argued that proportional harvest strategy—where a constant fraction of the population is harvested every year—has extremely weak theoretical underpinning, compared to strategies where harvesting is abandoned below a threshold density. The general result that thresholds are a key feature of precautionary harvest strategies where risk of extinction should be minimized while optimizing yield, was derived by approximating the stochastic dynamics by diffusion models. However, similar results have been reached in simulation studies (*e.g.*, Ludwig 1980, 1998; Quinn, Fagen, and Zheng 1990; Mace 1994), and it has been proposed that threshold strategies also perform well in the presence of critical depensation (a stock tends to collapse when below a critical size), catastrophes (sudden unexpected collapses in stock size), and with a heavy-tailed distribution of fluctuations in net reproduction (Ludwig 1998).

Another feature of marine resources and their environment that is not explicitly studied in the papers referred to above is temporal autocorrelation and dominance of low-frequency variability. It was observed some time ago (Steele 1985) that the dynamics of marine resources and their environment may be positively autocorrelated; *i.e.*, their dynamics are dominated by low-frequency variation and show "red" color (for a review, see Kaitala *et al.* 1997). Following this discovery, a number of papers have investigated how different harvesting strategies perform if the environmental variability is autocorrelated (*e.g.*, Koslow 1989; Walters and Parma 1996; Spencer 1997). The result seems to be contingent on the objective function used (*e.g.*, compare Walters and Parma (1996) with the studies by Koslow (1989) and Spencer (1997)). An important feature of red-shifted dynamics is that the variance of the stock increases (at least asymptotically) with time, which again means that population crashes can hardly be avoided (see Halley and Kunin (1999) for a discussion about 1/f-processes).

In this paper, we address the problem of harvesting resources that are inherently red. We show here that one such fishery is the Norwegian spring-spawning herring (*Clupea harengus*). The recruitment in this stock is highly variable, such that weak- and strong-year classes occur in an unpredictable manner. It has been argued that, in addition to the stochasticity, there is a density-dependent mechanism involved in the recruitment process (Patterson 1998). We study different management strategies and ask if any of them are capable of keeping the risk of stock collapse at a low level and, at the same time, allow for a reasonable high mean annual yield with low between-year variation. We show that neither the maximum yield nor the risk level differ much among the different harvesting strategies, but the variation in the annual yield is highest in the proportional threshold strategy. The proportional threshold strategy does not show the expected superiority when applied in the model of the

Norwegian spring-spawning herring fishery. We show that separating the harvest threshold from the risk level may increase the yield. However, increasing the threshold will increase the variability in the yield.

The Norwegian Spring-spawning Herring Fishery

The highly migratory Norwegian spring-spawning herring belongs to the list of the world's most valuable fish stocks (Bjørndal *et al.* 1997). Herring is a relatively long-lived species, the age span being up to 17 years. Mature herring spawn off the Norwegian coast in spring, followed by a feeding migration to the North Atlantic when the stock level is high enough.

The stock level (spawning stock biomass, SSB) of the Norwegian spring-spawning herring fluctuates considerably (figure 1A). Despite this, the stock has sustained significant fishing activity by Norwegian and Icelandic fishermen for more than a century. In the 1950s and 1960s, the stock was a major commercial species for Norway, Iceland, the Faroe Islands, and the Soviet Union. At the end of 1950s, the stock was about 10 million metric tons (figure 1A). The highest annual harvest (2 million tons) was recorded in 1966. For reasons that are beyond the scope of this paper, the

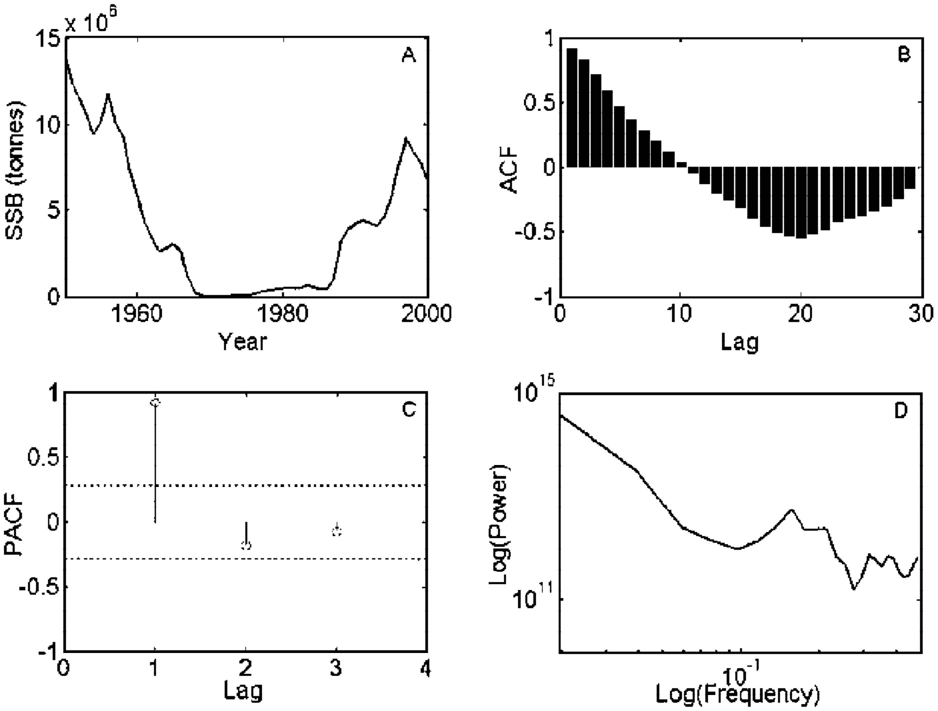

Figure 1. Spawning stock biomass (SSB), estimated by ICES (2001). (A) Time series showing stock dynamics. (B) Autocorrelation function. (C) Partial autocorrelation function. (D) Periodogram (the estimated power spectrum is not smoothed). In panels B-D, data have been $\log_e$-transformed, and a linear trend has been removed before analyses. The dotted lines in panel C define the 95% confidence interval.

stock collapsed over the next few years, and in 1970 a fishing moratorium was declared (Bjørndal *et al.* 2000). In the 1990s, the stock recovered and fishing was allowed again under international regulation. However, as of 2003 there is no international agreement on the management of this fishery.

Following tradition, we attempt to extract some insight into the dynamic processes in the fisheries using time series analysis. Autocorrelation function of the (detrended) stock dynamics suggest that the stock dynamics are positively autocorrelated (figure 1B), often referred to as red processes (Halley 1996). This is confirmed by the estimated power spectrum (figure 1D), which indicates that long-term fluctuations dominate in the dynamics, possibly with increasing variance. Such a process could be considered as one which experiences both high and low stock levels at irregular time intervals. Nevertheless, such a process is vulnerable to serious depletion of the resource. One of the central questions is whether there is a fishing policy with which the risk of major resource collapses can be minimized. Interestingly enough, the partial autocorrelation function of the stock experiences a positive feedback on one time step; that is, the stock process is of the first order (figure 1C). One may expect the lag structure to be richer in an age-structured population with delays in maturation.

Modelling Spring-spawning Herring Stock Dynamics

Following Conrad, Lopez, and Bjørndal (1998) we let:

$$X_{t+1} = (1 - M)(X_t - Y_t) + z_t R_{t+1}(X_{t-\tau}), \tag{1}$$

where X_t and Y_t are the stock biomass and yield at time t, respectively; M is the natural mortality; and $R_{t+1}(\cdot)$ are the recruits spawned at time $t + 1$ as a function of stock size τ years earlier. Stochasticity (z_t) affects the recruitment multiplicatively such that z_t is equal to 0, 1, or 2 with probabilities $P(0) = 0.1$, $P(1) = 0.8$, and $P(2) = 0.1$, which represents a white noise affecting the recruitment.

We have chosen a non-linear relationship between recruits-per-spawning biomass and the spawning biomass such that:

$$R_{t+1} = rX_{t-\tau}\left(1 - \frac{X_{t-\tau}}{K}\right), \tag{2}$$

where r is the intrinsic growth rate and K (“carrying capacity”) is the inverse of the strength of density dependence. There is considerable uncertainty about how to model the recruitment function (Patterson 1998) in the Norwegian spring-spawning herring fishery. Patterson (1998) estimated both the hump-shaped Ricker type and Beverton-Holt type function without being able to discern the better option. We have chosen here to work with the Ricker-type, non-linear recruitment function (2).

The model (1)-(2) gives rise to irregular unharvested stock dynamics as observed in data from wild populations (figure 2). It is the simplest presentation of the age-structured population dynamics of the Norwegian spring-spawning herring that catches the most important aspect for this study: the positive autocorrelation structure of the population dynamics representing the inherent uncertainty in the fate of the fishery. It may seem unfair to compare the properties of a time series produced by the model under no harvesting and a real data set from a harvested stock, since different harvesting strategies may change the autocorrelation structure of the population dynamics (Jonzén, Ripa, and Lundberg 2002). Patterson's work (1998) dealt with the data in this very fishery, which was later used for developing detailed age-structured models for the population dynamics by Touzeau *et al.* (2000), a work which was carried out in the research programme "The Management of High Seas Fisheries," funded by the European Commission (Bjørndal *et al.* 2000; Bjørndal and Gordon 2000; Lindroos and Kaitala 2000). When tested against the behavior of the more specific age-structured model, no major differences have been observed between the temporal structure of models (1)-(2) and the one presented in Touzeau *et al.* (2000).

Analyzing Different Harvest Strategies

The Norwegian spring-spawning herring fishery is annually regulated by setting a total allowable catch (TAC) based on biological information and guidelines from the International Council for the Exploration of the Seas (ICES) (Sandberg, Bogstad, and Røttingen 1998; ICES 2001). Such annual regulations are called harvesting *tac-*

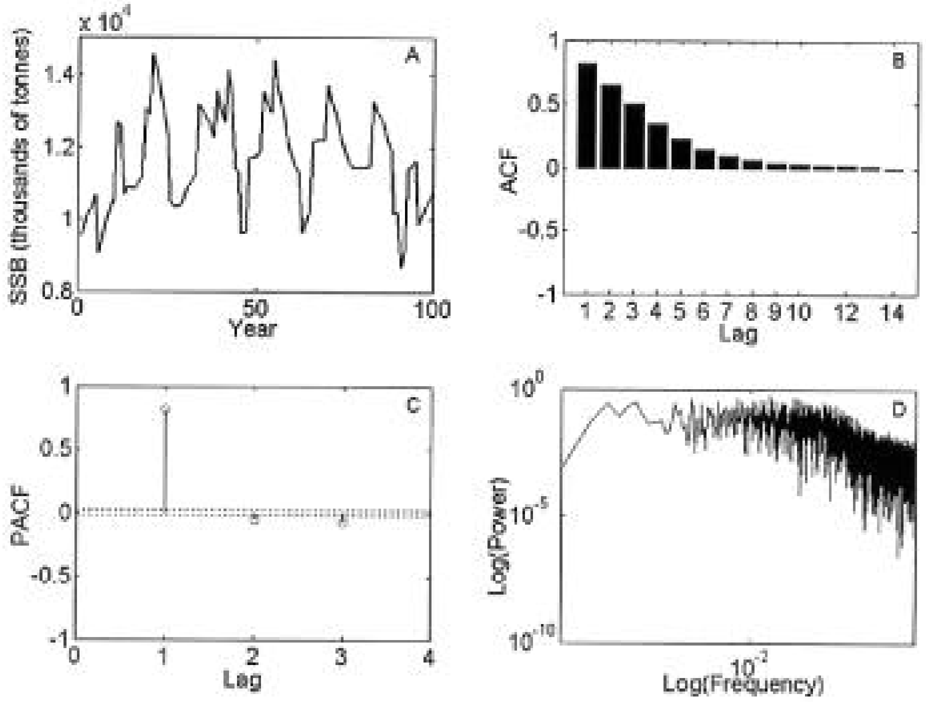

Figure 2. Model realization of an unharvested stock. We simulated equation (1) for 10,000 generations, discarding the first 1,000 generations. (A) Time series showing the stock dynamics. (B) Autocorrelation function. (C) Partial autocorrelation function. (D) Periodogram (the estimated power spectrum is not smoothed). In panels B-D, the Monte Carlo data have been $\log_e$-transformed before the analyses. The dotted lines in panel C define the 95% confidence interval. The parameters are $r = 0.4$, $K = 185{,}000$ (thousand tons).

tics (Hilborn and Walters 1992) and are the implementation of a harvesting *strategy*. In this paper, we will contrast the following harvesting strategies.

1. Proportional harvesting, defined as a constant proportion h of the biomass removed; that is, $Y_t = h\, X_t$.
2. Threshold harvesting, where a constant proportion of the biomass will be removed when the stock biomass is above a threshold, T; that is, $Y_t = h\, X_t$ when $X_t > T$, otherwise $Y_t = 0$.
3. Proportional threshold harvesting, where a constant proportion of the excess in stock biomass above a threshold is removed; that is, $Y_t = h\, (X_t - T)$ when $X_t > T$, otherwise $Y_t = 0$.

These alternative strategies are compared in terms of: (*i*) risk of quasi-extinction (see below), (*ii*) mean annual yield, and (*iii*) coefficient of variation of the yield.

For each fishing strategy and fishing pressure (= proportion harvested or asymptotic proportion in case of the proportional threshold harvesting) we ran equation (1) for 200 generations, iterated 500 times, and restricted the analysis to the last 100 generations to avoid the impact of transients. The risk of quasi-extinction was defined as the proportion of time spent below B_{lim} = 2.5 million tons. B_{lim} is a reference point for critical spawning stock biomass set by ICES (ICES 2001) and was also used as the biomass threshold in the threshold and proportional threshold harvest strategies. There has been a lot of uncertainty about the biomass in recent years (*e.g.*, compare assessment in Patterson (1998) and ICES (2001)). However, we were not interested in making a short-term prediction of spawning stock biomass, but rather in comparing the alternative harvesting strategies over a relatively long time span (100 years). We, therefore, initiated the spawning stock biomass (X) at the reference point equal to B_{pa} = 5 million tons (ICES 2001).

We also investigated how the alternative strategies perform in the presence of observation uncertainty, and we let the annual harvest be based on the observed biomass measured with an error following a log-normal distribution. Hence,

$$X_t^{obs} = X_t e^{(V_t \sigma_v - 0.5\sigma_v^2)}, \tag{3}$$

where V_t is a normally distributed random variable with mean zero and standard deviation σ_v (Hilborn and Mangel 1997). In the strategies above, this observation replaces the true value of the stock. Finally, we let the threshold take different values and studied the effect of alternative threshold levels on the performance of the proportional threshold harvest strategy with and without observation error. This was done by letting the threshold level vary between 2.5 and 6 (in steps of 0.25) million tons. For each threshold level, we calculated the value of the asymptotic harvest fraction that maximized the yield (h_{opt}), and the harvested biomass accordingly.

Results

In figure 3, we have plotted the risk estimate (the proportion of time the stock biomass spent below 2.5 million tons), the yield, and the coefficient of variation as a function of harvesting pressure for the three alternative strategies. By harvesting pressure, we refer to the actual fraction harvested, except for the proportional threshold strategy, where it equals the asymptotic harvest fraction. At an optimum harvest proportion (that is, the harvest proportion that maximizes the yield), the risks of quasi-extinctions are negligible in each strategy (figures 3A,B,C). Also, the maximum yields provided by each strategy are comparable, 800,000 tons/year for the proportional and threshold strategies (figures 3D,E) and 815,000 tons/year for the proportional threshold strategy (figure 3F). The maximum yield is obtained at harvest fraction *h* = 0.14 for the proportional and threshold strategies, and at *h* = 0.26 for the proportional threshold strategy. The risks of quasi-extinction are negligible for all strategies producing the maximum yield. The coefficient of variation (CV) in the yield shows slight differences between the strategies at the maximum yield—the proportional and the threshold strategies have the lowest CV (0.2) and the proportional threshold strategy has the highest CV (0.3, figures 3G,H,I).

The risk of quasi-extinction increases and the yield decreases abruptly with increasing harvest fraction in the proportional harvest strategy. Only a very low (< 0.3) fraction of the stock can be harvested under the proportional strategy (figure 3D), as the risk of quasi-extinction increases abruptly and the yield decreases abruptly around that value. The two other strategies are less sensitive to increasing harvest fraction. It is notable, however, that the proportional threshold strategy is characterized by low risk levels for all harvest fractions (figure 3C), providing at the same time a satisfactory yield (figure 3F). In a deterministic setting, the equilibrium stock is larger than zero if the harvest fraction is less than 0.29 (not shown).

So far, annual harvest has been based on the assumption that we can actually es-

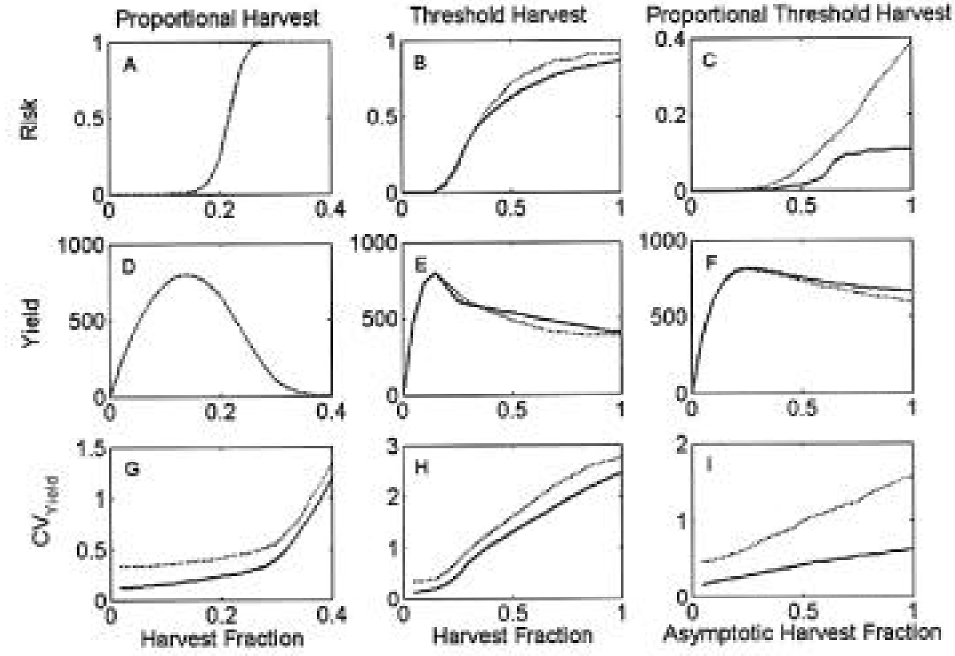

Figure 3. Comparison of three different harvesting strategies in terms of risk (A-C), average yield (D-F), and coefficient of variation of the yield (G-I). For each strategy and harvest fraction (or asymptotic harvest fraction), we ran 500 iterations of equation (1) for 200 years and analyzed the last 100 years. We also compared perfect observations of the stock biomass (solid lines) with the assumption of log-normal observation error with standard deviation equal to 0.3 (dotted lines). Note the different scale of the y-axes in panels A-C, D-F and G-I.

timate the stock biomass perfectly. The dotted lines in figure 3 show the effect of assuming a log-normal observation error ($\sigma_v = 0.3$) and basing the annual harvest on that estimate. Observation error has only a minor impact on the performance of the proportional harvest strategies, but clearly affects the threshold and proportional threshold strategies such that it increases the risk and decreases the average yield. Note, however, that these effects are visible only if the harvest proportion is increased beyond optimal levels. Note also that in comparison with the two former strategies, the proportional threshold strategy is still the most risk averse strategy and combines a relatively high average yield for all harvest fractions.

By increasing the threshold level and harvesting according to the asymptotic harvest fraction that maximizes the yield (h_{opt}), the risk of collapse can be reduced and the average yield will increase for the proportional threshold strategy (figures 4A,B). The maximum yield will be 830,000 tons/year and the optimal fraction will be $h_{opt} = 1$ when the threshold level is set to 5,000,000 tons. However, that is only true if the stock biomass is known. If there is considerable observation uncertainty, the risk increases with increasing threshold, but is still at a very low level (figure 4A). In either case, the yield becomes more variable and h_{opt} increases with a higher threshold (figures 4C-D). It is interesting to note that the threshold strategy provides the maximum yield equal to 820,000 tons/year with the same risk and variability properties as the proportional threshold strategy (not shown).

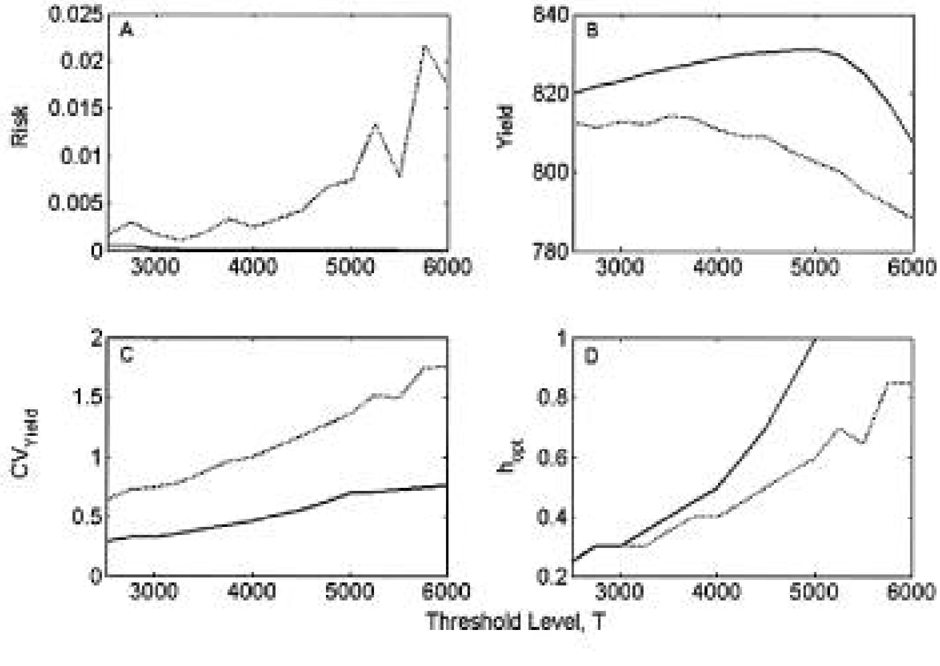

Figure 4. Comparison of different biomass thresholds, T, in terms of risk (A), average yield (B), coefficient of variation of the yield (C), and the asymptotic harvest fraction that maximized the yield, h_{opt}, (D). Only the proportional threshold harvest strategy was tested. For each T and h_{opt}, we ran 500 iterations of equation (1) for 200 years and analyzed the last 100 years. We also compared perfect observations of the stock biomass (solid lines) with the assumption of log-normal observation error with standard deviation equal to 0.3 (dotted lines).

Discussion

The Norwegian spring-spawning herring fishery is characterized by high-amplitude, low-frequency recruitment variability and can, in the terminology of Koslow (1989), be classified as a "high-risk fishery." Koslow (1989) concluded that neither a constant effort (proportional harvest in this paper) nor a constant escapement policy ("optimal harvest strategy" (Ludwig 1998); *i.e.*, all individuals above a threshold are harvested and no harvest occurs below the threshold) can be expected to maintain the long-term stability of such high-risk fisheries dominated by low-frequency variability. He further suggested that fishing strategies where fishing is abandoned below a threshold biomass are preferable in terms of minimizing the risk of stock collapse. These properties of the proportional threshold harvest strategy have been demonstrated before (Lande, Engen, and Sæther 1995; Lande, Sæther, and Engen 1997), and it is a very general appreciation that risk-averse harvesting strategies in stochastic environments should involve a density or biomass threshold below which no harvest takes place (Ludwig 1980; Lande, Engen, and Sæther 1995; Lande, Sæther, and Engen 1997; Ludwig 1998). This view is only partly confirmed in this study of the Norwegian spring-spawning herring fishery. We found no such differences between the strategies when maximum yield is the target—the differences become true only when the stocks are overharvested.

Ludwig (1998) studied different harvest strategies in fisheries, including complications such as: critical depensation, catastrophes, and heavy-tailed distribution of fluctuations. He studied three different strategies: (1) the "optimal strategy," defined as choosing a target biomass and instantaneously harvesting the biomass exceeding the target level if above the target level, and abandoning harvesting when below the target level; (2) the "constant exploitation rate strategy," defined as choosing a fraction and harvesting that fraction of the stock annually; (3) the "constant harvest strategy," defined as choosing a harvest size (catch) and taking that harvest annually. The optimal strategy (1) corresponds to the bang-bang optimal control derived by Clark (1976), later extended to a stochastic setting by Reed (1979) and Ludwig (1979). It also mimics proportional threshold harvesting, where all of the excess in stock biomass above a threshold is removed. The two strategies differ, however, in the sense that we did not choose the threshold by optimizing the yield. Instead, we compare the yields and risks for the whole range of harvest fractions to get a better picture of the performance of the harvest strategies. Constant exploitation rate strategy (2) corresponds to our proportional strategy. We did not consider constant harvest strategy (3), as it is known to perform poorly (Ludwig 1998). In our simulations, the maximum yield equal to 800,000 tons/year is obtained for the proportional harvesting (with risk level 0), and 815,000 tons/year for the proportional threshold harvesting strategy when the threshold level is 2.5 million tons. When the threshold level is optimized in the proportional threshold strategy (B_{opt} = 5.1 million tons, figure 4B), the optimal proportion becomes one (figure 4D). Thus, in this case the proportional threshold harvesting strategy is in agreement with the optimal strategy (1) studied by Ludwig (1998). However, when we have observation error involved in the fishery model, the optimal threshold may be taken as B_{opt} = 3.5 million tons, and the optimal proportion becomes $h = 0.4$ (figure 4). Thus, in the presence of observation error, the proportional threshold harvesting strategy differs from the optimal harvest strategy. Thus, whereas Ludwig (1998) observes a clear advantage in using the optimal strategy as compared to the constant exploitation rate strategy, we cannot see that much difference between the proportional strategy and the proportional threshold strategy. Overall, we cannot confirm the view that the proportional threshold strategy, or the optimal harvest strategy, would be a superior strategy in each fishery. A more general proportional threshold harvesting strategy is, however, better in the presence of observation uncertainty than the optimal strategy. This, again, may depend on the form of the observation error.

One example of a proportional threshold harvest strategy is the linear adaptive TAC policy studied by Conrad, Lopez, and Bjørndal (1998). They combined a bioeconomic optimum with safe minimum biomass level (SMBL) with the adaptive TAC policy. The SMBL in their study corresponds to the threshold level, T, used here. Such a policy should result in an optimum stock level. In a varying fishery, the TAC policy results in a stock level distribution which varies around the optimum level. The parameters were derived so as to optimize the bioeconomic optimum under deterministic conditions. The specific policy derived was equivalent to proportional threshold harvesting with $T = 2.5$ million tons and $h = 0.334$. Our results confirm that the adaptive TAC policy will result—even under a highly variable fishery—in high yield, low risk of quasi-extinction, and relatively low variance in yield. Depending on the degree of uncertainty in the stock biomass estimate, the threshold level, T, could be set above 2.5 million tons to increase the average yield (figure 4B). At the same time, the asymptotic harvest fraction that maximizes the yield (h_{opt}) would increase. It is also interesting to note that in our simulations, increasing the fraction of stock harvested does not decrease the yield much from the optimum, and the risk of extinction increases only marginally. Finally, the proportional strategy performed better than the alternative harvesting strategies when the annual harvest was based on biomass estimates with considerable observation error.

Touzeau *et al.* (2000) carried out a biological and economic risk assessment in Norwegian spring-spawning herring using a detailed age-structured model with Beverton-Holt and Ricker stock recruitment functions. It is worth noting that they used a model which is comparable with the proportional harvesting strategy only. They found that the stock dynamics may be sensitive to model parameters. For example, changes in juvenile natural mortality may produce notable changes in the equilibrium population size. Thus, the management of the spawning areas should be of importance for the management of the fisheries as a whole. Their results also confirm the biological risk in harvesting Norwegian spring-spawning herring. The maximum sustainable yield is obtained under equilibrium conditions when fishing mortality is about 0.2. When stochasticity is taken into account, the risk of stock collapsing below the critical value fishing mortality equal to 0.1 is 50%. For fishing mortality equal to 0.2, the risk immediately increases to 100%. Thus, these results, which are in agreement with our results (figure 3A), underline the importance to apply adaptive proportional threshold strategy in maximizing the yield and minimizing the biological risk of quasi-extinctions.

Our results may indicate why fisheries scientists continue to insist that fishing mortality be reduced in real fisheries. If overfishing can be avoided, then it does not matter too much which one of the fishing strategies should be used. However, difficulties will arise when social and other pressures inevitably lead to higher harvest rates and to other deviations from the fishing policy. We have not dealt with this issue. The reasons are manifold, some of which are structural and others that are related to the enforcement of the fisheries policy. In a fishery like the present one, the international agreements are often negotiated annually, and there is no guarantee that they will succeed. Consequently, a failure in reaching an international agreement will, in the worst case, lead in an open-access fishery. Second, although a well-defined fishery policy would be agreed upon, violations against the agreement may occur. The threshold limit may not be followed, or the fraction of the stock harvested may be exceeded. While acknowledging the problems faced in real fisheries policy, we have not taken a position in the present paper as to how best deal with these problems.

To summarize, we found that there are no significant differences between the three harvesting strategies compared. The threshold strategy and the proportional threshold strategy provide 2.5% higher average maximum yield than the proportional strategy, at the expense of having higher variation in the yield. On the basis of our study, it becomes a matter of taste and choice between a slightly higher maximum yield or a slightly lower variability in the yield when choosing a harvest strategy. This conclusion is only valid in the absence of overharvesting. In practice, however, most fish stocks tend to be overexploited (Ludwig, Hilborn, and Walters 1993), and from that perspective, the choice between strategies may not be "a matter of taste." Analysis of this fishery's sensitivity to overexploitation is needed to draw further conclusions. Considering that the Norwegian spring-spawning herring stock has collapsed under exploitation in recent history, we feel that the results of this and previous studies should be taken seriously when designing long-term strategies for the exploitation of this fishery.

References

Bjørndal, T., and D.V. Gordon. 2000. The Economic Structure of Harvesting for Three Vessel Types in the Norwegian Spring-spawning Herring Fishery. *Marine Resource Economics* 15(4):281–92.

Bjørndal,T., A.D. Hole, W.M. Slinde, and F. Asche. 1997. Norwegian Spring Spawning Herring—Some Biological and Economic Issues. Centre for Fisheries Economics, Norwegian School of Economics and Business Administration, Discussion Paper No. 3/1997, Bergen 45 pp.

Bjørndal, T., V. Kaitala, M. Lindroos, and G. Munro. 2000. The Management of High Seas Fisheries. *Annals of Operations Research* 94:183–96.

Clark, C. 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. New York: Wiley.

Conrad, J.M., A. Lopez, and T. Bjørndal. 1998. Fishery Management: The Consequences of Honest Mistakes in a Stochastic Environment. SNF-working paper 27/98. Foundation for Research in Economics and Business Administration, Bergen, Norway.

Engen, S., R. Lande, and B.-E. Sæther. 1997. Harvesting Strategies for Fluctuating Populations Based on Uncertain Population Estimates. *Journal of Theoretical Biology* 186:201–12.

Halley, J.M. 1996. Ecology, Evolution, and 1/f Noise. *Trends in Ecology and Evolution* 11:33–8.

Halley, J.M., and W. Kunin. 1999. Extinction Risk and the 1/f Family of Noise Models. *Theoretical Population Biology* 56:215–39.

Hilborn, R., and M. Mangel. 1997. *The Ecological Detective. Confronting Models with Data*. New Jersey: Princeton University Press.

Hilborn, R., and C.J. Walters. 1992. *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. New York: Chapman and Hall.

Hutchings, J.A. 2000. Collapse and Recovery of Marine Fishes. *Nature* 406:882–85.

ICES 2001. Report of the ICES Advisory Committee on Fishery Management, 2001. ICES Cooperative Research Report No.246. Copenhagen, Denmark.

Jonzén, N., J. Ripa, and P. Lundberg. 2002. A Theory of Stochastic Harvesting in Stochastic Environments. *American Naturalist* 159:427–37.

Kaitala, V., P. Lundberg, J. Ripa, and J. Ylikarjula. 1997. Red, Blue and Green—Dyeing Population Dynamics. *Annales Zoologici Fennici* 34:217–28.

Koslow, J.A. 1989. Managing Nonrandomly Varying Fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* 46:1302–08.

Lande, R., S. Engen, and B.-E. Sæther. 1994. Optimal Harvesting, Economic Discounting and Extinction Risk in Fluctuating Populations. *Nature* 372:88–90.

___. 1995. Optimal Harvesting of Fluctuating Populations with a Risk of Extinction. *American Naturalist* 145:728–45.

Lande, R., B.-E. Sæther, and S. Engen. 1997. Threshold Harvesting for Sustainability of Fluctuating Resources. *Ecology* 78:1341–50.

Lindroos, M., and V. Kaitala. 2000. Nash Equilibria in a Coalition Game of the Norwegian Spring-spawning Herring Fisheries. *Marine Resource Economics* 15(4):321–39.

Ludwig, D. 1979. Optimal Harvesting of a Randomly Fluctuating Resource. I: Application of Perturbation Methods. *Society for Industrial and Applied Mathematics Journal of Applied Mathematics* 37:166–84.

___. 1980. Harvesting Strategies for a Randomly Fluctuating Population. *Journal du Conceil pour l'Exploration de la Mer* 39:168–74.

___. 1998. Management of Stocks that May Collapse. *Oikos* 83:397–402.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, Resource Exploitation and Conservation: Lessons from History. *Science* 260:17–36.

Ludwig, D., M. Mangel, and B. Haddad. 2002. Ecology, Conservation, and Public Policy. *Annual Review in Ecology and Systematics* 32:481–517.

Mace, P.M. 1994. Relationships Between Common Biological Reference Points Used as Thresholds and Targets of Fisheries Management Strategies. *Canadian Journal of Fisheries and Aquatic Sciences* 51:110–22.

Mangel, M. 1985. *Decision and Control in Uncertain Resource Systems*. New York: Academic Press.

Patterson, K.R. 1998. Biological Modelling of the Norwegian Spring-spawning Herring Stock. Report 1, Fisheries Research Services, Aberdeen, Scotland.

Pitcher, T.J., P.J.B. Hart, and D. Pauly, eds. 1998. *Reinventing Fisheries Management*. Dordrecht: Kluwer Academic Publishers.

Quinn, T.J. II, R. Fagen, and J. Zheng. 1990. Threshold Management Policies for Exploited Populations. *Canadian Journal of Fisheries and Aquatic Sciences* 47:2016–29.

Reed, W.J. 1979. Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models. *Journal of Environmental Economics and Management* 6:350–63.

Sæther, B.-E., S. Engen, and R. Lande. 1996. Density-Dependence and Optimal Harvesting of Fluctuating Populations. *Oikos* 76:40–6.

Sandberg, P., B. Bogstad, and I. Røttingen. 1998. Bioeconomic Advice on TAC - the State of the Art in the Norwegian Fishery Management. *Fisheries Research* 37:259–74.

Spencer, P.D. 1997. Optimal Harvesting of Fish Populations with Nonlinear Rates of Predation and Autocorrelated Environmental Variability. *Canadian Journal of Fisheries and Aquatic Sciences* 54:59–74.

Steele, J.H. 1985. A Comparison of Terrestrial and Marine Ecological Systems. *Nature* (London) 313:355–58.

Touzeau, S., V. Kaitala, M. Lindroos, and J. Ylikarjula. 2000. Economic and Biological Risk Analysis of the Norwegian Spring-Spawning Herring Fishery. *Annals of Operations Research* 94:197–217.

Walters, C.J., and A.M. Parma. 1996. Fixed Exploitation Rate Strategies for Coping with Effects of Climate Change. *Canadian Journal of Fisheries and Aquatic Sciences* 53:148–58.