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Evaluation of harvest control rules: simple one-parameter vs. complex multi-parameter strategies

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Abstract

Harvest control rules (HCR) are sets of well-defined rules that can be used for determining annual fish catch quotas. If a management policy can be expressed as a HCR, then the HCR provides means to determine the total allowable catch unambiguously. In order to improve certain aspects of the performance for these rules, rules of increasing complexity have been suggested for fish stocks both in Europe and in North America. But is this complexity necessarily better? Are simple strategies outdated? "Traditional" harvesting strategies (i.e. constant harvest rate, fixed quota and constant escapement strategies) are simple HCRs with only one control parameter (i.e. target harvest rate, catch and escapement, respectively). "Complex" harvest control strategies are here defined as a multi-parameter HCR. In this study, three criteria (average catch and its coefficient of variability and risk of population abundance below a minimum acceptable level) are used to judge the performance of traditional and complex HCRs, utilizing a set of stochastic age-structured population models that mimic dynamics of fish populations. The traditional and complex HCRs are then evaluated against each other, paying particular attention to the trade-offs among the performance criteria.

Keywords: harvest control rules, harvesting strategies, single-parameter, multi-parameter, stochastic population models, stochastic noise, age-structured models

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1. INTRODUCTION

Fair and clearly specified management policy is in the interest of all stakeholders of the world's fish resources. Harvest control rules are an attempt to formulate management strategies that fulfill a clear objective, and that can be tailored towards fairness.

Harvest control rules (HCR) are sets of well-defined rules that can be used for determining annual catch quotas (Cooke 1999, Johnston et al. 2000, Restrepo & Powers 1999). If a management policy can be expressed as a HCR, then the HCR provides means to determine the total allowable catch unambiguously. In order to improve certain aspects of performance of these rules, rules of increasing complexity have been suggested for the fish stocks both in Europe (i.e., within the International Council for the Exploration of the Sea, ICES) and in North America. But is this complexity necessarily better? Are simple strategies outdated?

"Traditional" harvesting strategies, e.g., constant harvest rate, fixed quota and constant escapement strategies (Hilborn & Walters 1992), are simple HCRs with only one control parameter (for the above mentioned strategies, target harvest rate, target catch and target escapement, respectively). "Complex" harvest control rules are defines here as rules with more than one control parameter. Although there is no upper limit for the number of control parameters, considering more than three parameters is probably seldom practical.

This paper presents the first results from our project that aims at gaining some general insights on the merits of various harvest control rules. Our approach is to investigate the performance of harvest control rules using a simple, generic model that still can capture the essence of fish population dynamics, as opposed to a more narrow focus on a specific case study. We hope that this will lead into a better understanding of what can be gained by adding new layers of complexity to the classic, well-studied harvest strategies that have only one control parameter (Hilborn & Walters 1992, Restrepo & Powers 1999).

In this study, three criteria -average catch and its variability, and risk of population abundance below minimum acceptable level- are used to judge the performance of traditional and complex HCRs, utilizing a set of stochastic age-structured population models that mimic dynamics of fish populations. The traditional and complex HCRs are then evaluated against each other, paying particular attention to the trade-offs among the performance criteria.

2. MATERIALS & METHODS

2.1 Population & Survival Equations

The population equations describe the model of a theoretical fish stock made up of three age classes:

$$\begin{aligned} N_{0(year)} &= f_1 * N_{(year)} + f_2 * N_{2(year)} \\ N_{1(year+1)} &= s_0 * N_{0(year)} \\ N_{2(year+1)} &= s_1 * N_{1(year)} + s_2 * N_{2(year)} \end{aligned} \qquad (1)$$

Where, f is fecundity and s is survival. Any fish older than two years continued to belong to the N_2 age class throughout its life span.

The Beverton-Holt equation for density dependency [which can not produce chaos] is used for the survival of N_0. Stochasticity is added to the newborn survival as an element from birth to the age of one year of environmental variability, or "noise".

$$\begin{aligned} s_0 &= \exp(-M_0)/(1+k*N_{0(year)}) * \text{Norm}(0, \sigma^2_S) \\ s_1 &= \exp(-(M_1 + F_1)) \\ s_2 &= \exp(-(M_2 + F_2)) \end{aligned} \qquad (2)$$

where k is a parameter describing the strength of density dependence, Norm(0, σ^2_S) is a normally distributed random deviate with zero mean and variance σ^2_S, M_0, M_1 and M_2 are instantaneous natural mortality rates at ages 0, 1 and 2, respectively, and F is instantaneous fishing mortality rate. No fishing mortality occurs before the age of 1 year.

In order to mimic imperfect control of fishing mortality, stochasticity was also added to F_1 and F_2 values in some simulations. In these cases, noise was added multiplicatively, with Norm(1, σ^2_F) being a normally distributed non-negative random deviate with one as the mean and variance σ^2_F.

2.2 Harvest Control Rules (HCRs)

Three different types of harvest control rules were used in the model and are illustrated in Figure 1. Type 1 was a one parameter HCR in which the fishing mortality (F_{const}) is constant. Type 2, had two control parameters: the threshold biomass parameter (B*) and the corresponding fishing parameter (F_{max}). Similarly, Type 3 had two control parameters: F_{max} and B*.

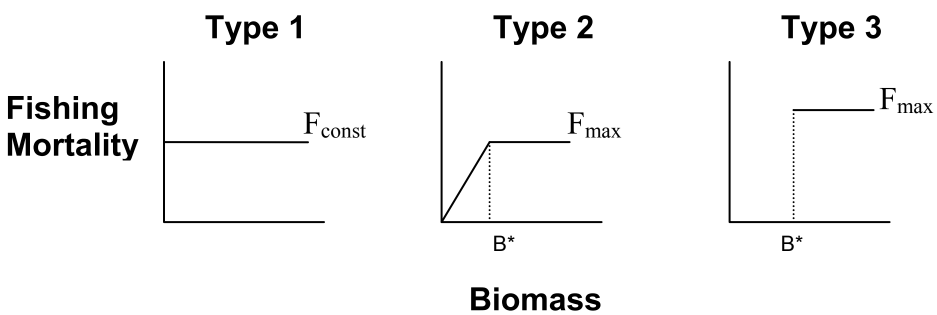

FIGURE 1: The three harvest control rule types used in the simulations.

2.3 Simulation Procedures

Fortran was the computer language chosen for implementing the model. The model was run for a time cycle of 50,000 years. The first hundred years were used to allow the fish population to reach a stochastic steady state. Years 100-50,000 were then used to analyze the performance of the three different harvest control rules implemented.

The three main criteria used to rate each harvest control rules' performance were: average yield, coefficient of variation in yield (defined as the standard deviation/average yield * 100), and "risk". Risk was defined as the probability of population biomass being below a minimum acceptable level, here set to 10% of "virgin" biomass, i.e., average biomass in absence of fishing.

Stochasticity in the model was controlled by adjusting the variance levels to the s_0 and to the fishing mortality levels. Six simulations were conducted using the described model, each with different levels of stochastic "noise". Parameters used in the *Fortran* main code are shown in Table 1.

TABLE 1: The population model's parameters and their values.

weight of age 1 fish	1
weight of age 2 fish	3
natural mortality at time 0	2
natural mortality at time 1	0.4
natural mortality at time 2	0.2
fecundity at time 1 proportional to the weight of N1	10000
fecundity at time 2 proportional to the weight of N2	30000
k used in Beverton-Holt s0	1

3. RESULTS

Table 2 shows the HCR performances of the three main criteria for each of six simulations with no constraints given to any of the criteria. The variance levels refer to the addition of stochasticity to the model; either to the new recruits' survival (s_0) or to the fishing mortality (F). As s_0 variance increases, so does the performance of multi-parameter strategies. An exception to this statement can be seen in simulations 5 and 6 where it becomes difficult to distinguish much difference between the criteria values for Type 1 and Type 2.

TABLE 2: Summary of the simulations for each harvest control type in an unconstrained situation.

SIMULATION	VARIANCE LEVELS	HCR Type 1			HCR Type 2			HCR Type 3		
		MAX YIELD	CV	RISK	MAX YIELD	CV	RISK	MAX YIELD	CV	RISK
1	σS = 0.2	18.7	10.7	0	18.7	10.8	0	21.2	138.8	0
2	σS = 0.4	19.9	22.2	0.002	19.9	22.2	0	22.2	137.4	0
3	σS= 1.0	30.3	68.6	8.6	30.6	69.6	8.5	30.4	69.0	0.004
4	σS= 0.3, σF = 0.1	21.3	42.4	0.01	21.7	59.6	1.33	22.5	142.6	0
5	σS = 0.5, σF = 0.2	23.6	63.4	4.8	24.2	83.0	3.7	25.0	141.8	0.006
6	σS = 0.4, σF = 0.05	22.5	43.4	1.4	23.0	62.8	0.8	23.9	144.0	0

When comparing single criteria performances, Type 3 has the highest yield and lowest risk in each simulation at the cost of the highest CV in yield. Type 1 shows best results when looking only at CV. The CV is the criterion that distinguishes the three HCRs while the yields are quite similar for each of the types. Type 1 and Type 2 perform similarly when considering both yield and CV.

Each of the simulations was also run in a constrained situation, seen in Table 3. The constrained situation would not allow a harvest control rule that gave CV values were above 20.0 or risk values above 1.0. In simulations 1 and 2, this resulted in virtually identical performance for all considered HCR types. In other simulations, no HCR satisfying the constraints were found.

TABLE 3: Summary of the simulations for each harvest control type in a constrained situation which was defined with maximum CV values of 20 and 1.0 for risk.

SIMULATION	VARIANCE LEVELS	HCR Type 1			HCR Type 2			HCR Type 3		
		MAX YIELD	CV constrained	RISK	MAX YIELD	CV constrained	RISK	MAX YIELD	CV constrained	RISK
1	σS = 0.2	18.7	10.7	0	18.7	10.8	0	18.7	10.7	0
2	σS = 0.4	19.3	19.9	0	19.3	19.6	0	19.2	19.6	0
3	σS= 1.0	0.0	NA	NA	0.0	NA	NA	0.0	NA	NA
4	σS= 0.3, σF = 0.1	0.0	NA	NA	0.0	NA	NA	0.0	NA	NA
5	σS = 0.5, σF = 0.2	0.0	NA	NA	0.0	NA	NA	0.0	NA	NA
6	σS = 0.4, σF = 0.05	0.0	NA	NA	0.0	NA	NA	0.0	NA	NA

Harvest control rule Type 1 (constant fishing mortality level) showed increasing CV and risk with increasing maximum yields. The maximum yields for Type 1 and 2 were very similar for each of the simulations, differing only in CV and risk. Figure 3 shows the optimal fishing parameter level for HCR Type 1 in the sixth simulation.

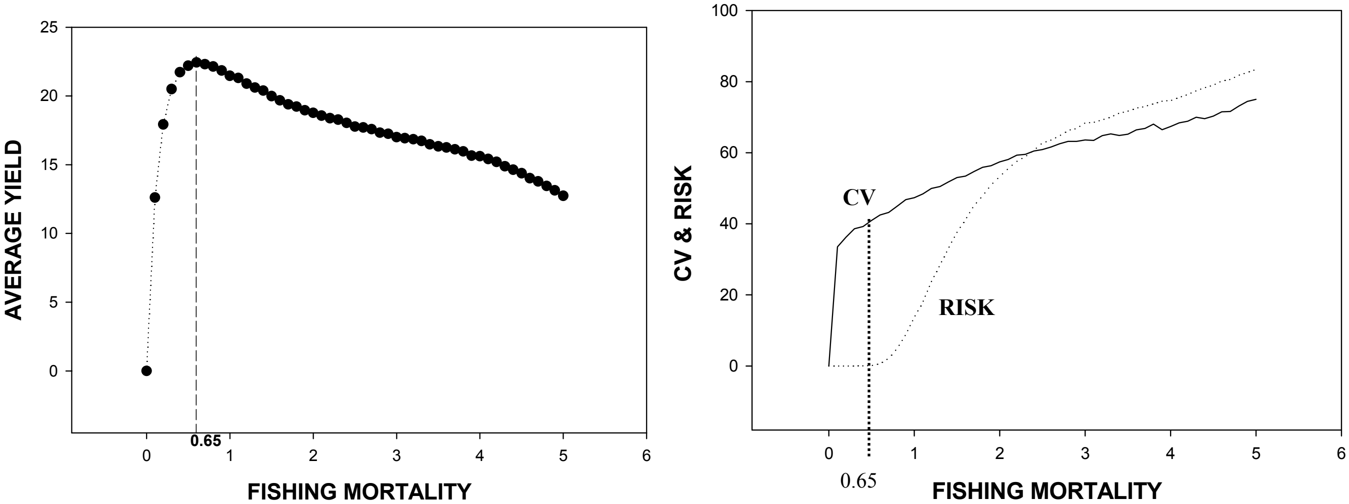

FIGURE 3: Simulation results for control parameter (constant F) and the corresponding average yield for Type 1 harvest control rule. CV and risk are also shown with fishing mortality. Results plotted show σ_S = 0.4 and σ_F = 0.05. The highest yielding fishing mortality is shown at 0.65 with corresponding CV and risk values of 43.4 and 1.4, respectively.

Figure 4 illustrates the sixth simulation for HCR Type 2. Characteristic for this HCR type is that if threshold biomass is above average biomass, yield becomes almost independent of the actual parameters B* and F_{max}, as long as they result in a similar slope below B*. This explains why the yield surface has a ridge (Figure 4), along which the yield is very close to the maximum sustainable yield.

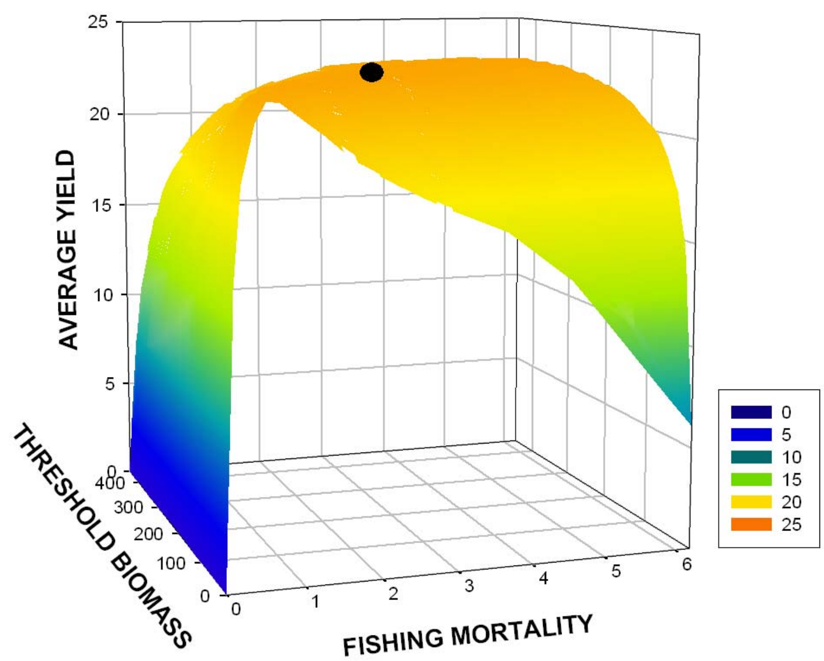

FIGURE 4: Three dimensional graph of Type 2 HCR in simulation number 6, where σ_S = 0.4 and σ_F = 0.05. The black circle indicates the best performing threshold biomass B* of 300 with a corresponding fishing mortality level F_{max} at 3.6 with corresponding CV and risk values of 62.8 and 0.8, respectively.

In all simulations except one (simulation 3, σ_S= 1.0), harvest control rule Type 3 had the highest CV values, indicating elevated fluctuations of the mean yield each year. In these five simulations, the CV values had a mean of 141% variation of the mean yield. However, HCR Type 3 had the lowest risk in all six simulations and the highest maximum yield in five of the six simulations. Figure 5 illustrates the sixth simulation graphically.

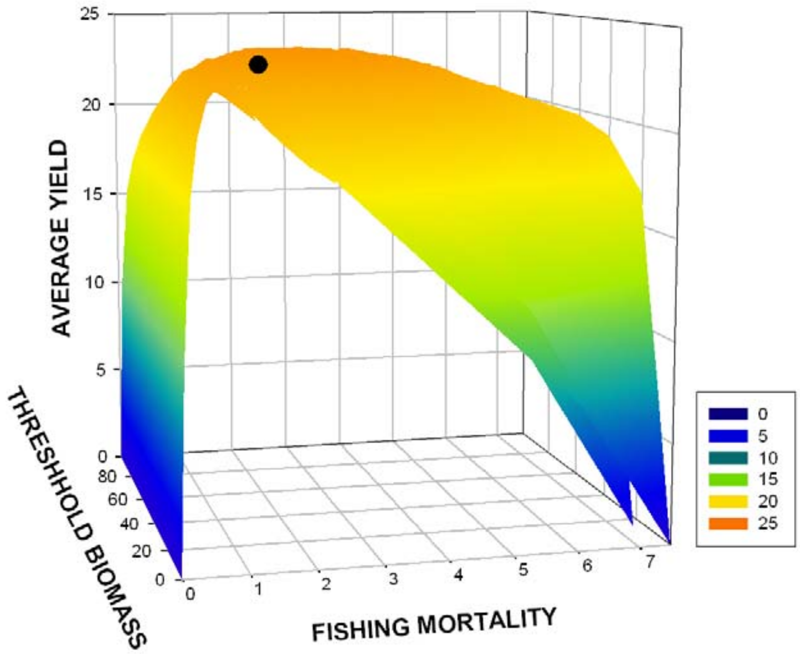

FIGURE 5: Three dimensional graph of Type 3 HCR in simulation number 6, where $\sigma_S = 0.4$ and $\sigma_F = 0.05$. The black circle indicates the best performing threshold biomass B* of 40 with a corresponding fishing mortality level F_{max} of 2.3 with corresponding CV and risk values of 144.0 and 0, respectively.

4. DISCUSSION

We have considered three performance criteria: average yield, variability in yield (measured by coefficient of variability), and risk of biomass being below a minimum acceptable level. These reflect different aspect of performance of the management strategy. Consequently, fisheries managers, fishermen and other stakeholders probably would value the criteria differently. A utilitarian fisheries manager would perhaps value high average yield most, whereas fishermen would also set heavy weight also on variability of the annual catches. A conservationist could be concerned, above all, on having as small risk of biomass being below a minimum acceptable level as possibly.

The multi-parameter HCR Type 3 performed best considering yield and risk, but worst when considering CV in yield. Therefore, the fishing fleet would not be able to rely on this one resource. The single-parameter HCR Type 1 and the multi-parameter HCR Type 2 had only marginally lower yield, but much lower variability of yield. On the other hand, the risk of biomass being below a minimum acceptable level was higher than with the HCR Type 3. Thus, the eventual choice among the three strategies would critically depend on the weighting of the various performance criteria. In particular, whether better performance is gained with a complex or a simple harvest control rule depends on the relative importance set on average yield versus year-to-year stability in yield.

In short, the preliminary set of simulations carried out for this paper show that the best performing HCR is dependent on the levels of variance of the stochastic noise given to the model. This suggests that environmental and/or biological variation of an ecosystem or fish population need to be studied and known before the appropriate application of a one or multi-parametric harvest control rule. With this said, proper knowledge of the population and its cohorts through up-to-date stock surveys as well as their connections to environmental factors (e.g. temperature) and to ecosystem in which it lives is reinforced when considering optimal harvesting management. Moreover, data from the fishing fleet is important to determine by-catch and fishing variance to include in the criteria to construct an optimal HCR. We will carry out more extensive simulations as the next step in our work in order to check the robustness of the results emerging in our preliminary simulations. This will also help us gain a more refined picture of the relationships between the various model parameters describing the biology of a stock and its environment, and the performance of various harvest control rules.

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