

Optimal fishery management under environmental uncertainties

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Preface

The present thesis is a collection of three papers written at the University of Kiel during my period as a doctoral candidate at the Institute of Economics. The first two papers are joint work with Martin Quaas. The paper “Does the stock size of a fish stock increase with environmental uncertainties?” has been published in *Environmental and Resource Economics* (2013). My contribution mainly includes the model set-up, the analysis of the quantitative examples and most of the writing. The paper “Optimal harvest control rules for stochastic fish stocks when stakeholders are risk averse” has been submitted for publication in *Marine Resource Economics* and is currently under review. Here, I contribute to the paper by doing the estimations and numerical calculations of the application and most of the writing. The third paper is the single-authored paper “How to deal with ocean acidification in fisheries management - An example on Norwegian coastal cod”.

Introduction

Uncertainty plays an important role in almost all economic decisions. This particularly holds for the management of marine fish stocks. "Virtually everything about a marine population is poorly known; some aspects may be almost completely unknown, even for important species with long history of fishing. Past and present stock abundance, and biological characteristics such as growth, natural mortality and reproduction rates, though important to management decisions, are usually highly uncertain."¹

Although fisheries assessment methods are being continuously improved the uncertainties inherent in fishery models will never be completely solved and especially stock growth will to some extent remain unpredictable. Indeed, the development of the fish stock, i.e. the sum of reproduction, growth in weight and length, and natural mortality, is highly dependent on environmental conditions, e.g. on the chemical composition of the seawater like pH-value, oxygen concentration and salinity, on the temperature and currents, but also on the interaction with other species in the ecosystem.² These conditions fluctuate and are often unknown to the fishery manager at the time the management decision is made. Hence, the presence of uncertainties in the environmental conditions should be considered in the management of fish stocks.

In my dissertation I examine how the optimal fishery management will be influenced by uncertain environmental conditions. It is a cumulative work consisting of three paper projects dealing with different aspects of optimal fishery management under environmental uncertainties.

The first paper "**Does the optimal size of a fish stock increase with environmental uncertainties?**", which is a joint work with Martin Quaas, compares the optimal management under stochastic stock growth with the optimal

¹Clark, C.W. (2006) *The Worldwide Crisis in Fisheries - Economic Models and Human Behavior*. Cambridge university press.

²Hilborn, R., Walters, C.J. (1992) *Quantitative Fisheries Stock Assessment - Choice, Dynamics and Uncertainty*. Kluwer Academic Publishers.

management in a deterministic benchmark model. We found that the optimal stock size in a stochastic stock growth model could be higher or lower than in the deterministic setting, depending on the prudence of the value function, which in turn depends on the biomass growth function, the profit function and the von-Neumann-Morgenstern utility function of the fishermen. This paper contributes to the already broad body of literature dealing with optimal resource management under stochastic stock growth by providing a deeper understanding and an intuitive explanation of the influence of environmental uncertainties on the optimal fishery management. Furthermore by applying our model to two existing fisheries, incorporating the estimated variance in stock growth and the estimated cost function, we provide valid results for fishery management.

The second paper "**Optimal harvest control rules for stochastic fish stocks when stakeholders are risk averse**" is a joint work with Martin Quaas. In this paper we determine optimal harvest rules for different degrees of risk aversion among stakeholders, precisely among fishermen and consumers. With a higher degree of risk aversion, the optimal harvest control rule becomes flatter and shifts more uncertainty from harvest to the stock. Mean and coefficient of variation (CV) of harvest will decrease, while the CV of the resource stock will increase. The effect of risk aversion on the mean resource stock is ambiguous. Risk aversion in stochastic fishery models has mostly been neglected in the literature with only very few articles dealing with specific aspects of risk aversion. We further fill the gap by deriving analytical solutions for a class of specific discrete time models, and numerical results in an application to the Eastern Baltic cod fishery.

In my last paper "**How to deal with ocean acidification in fishery management - an example on Norwegian coastal cod**" I consider a special case of uncertainty in environmental conditions, i.e. the influence of ocean acidification on optimal fishery management. I consider how results from laboratory-based experiments on the physiological effects of decreasing pH-values could be scaled to population processes as a part of an ecological-economic model. In particular I demonstrate a way to include an acidic-induced higher mortality in early-life stages

of a fish into the stock-recruitment relationship and thus into an age-structured fishery model. Research on the economic consequences of ocean acidification is quite new and to my knowledge this is the first paper which studies the optimal fishery management under ocean acidification.

All three papers demonstrate that uncertainty in environmental conditions will influence the optimal fishery management. The numerical applications have shown that the optimal feedback rule with stochastic stock growth will not differ significantly from the one in a deterministic setting. But environmental uncertainty has a great effect on the inter-temporal harvesting possibilities and thus plays an important role for risk-averse stakeholders. Risk aversion will shift risk from harvest to stock and will therefore smooth out extreme fluctuations in inter-annual harvest rates. While in the first two papers uncertainty is represented by an independent identically distributed random variable, other forms of uncertainty could have deviating effects on the optimal fishery management. The effect of exacerbating environmental conditions on harvesting possibilities e.g. I have studied in my third paper.

Further research will be needed by including environmental uncertainties in a greater context, adding e.g. multiple uncertainties, ecosystem interactions, and evolving climate change, to improve the basis of fisheries management recommendations.

Does the optimal size of a fish stock increase with environmental uncertainties?*

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September 29, 2012

Abstract. We analyze the effect of environmental uncertainties on optimal fishery management in a bio-economic fishery model. Unlike most of the literature on resource economics, but in line with ecological models, we allow the different biological processes of survival and recruitment to be affected differently by environmental uncertainties. We show that the overall effect of uncertainty on the optimal size of a fish stock is ambiguous, depending on the prudence of the value function. For the case of a risk-neutral fishery manager, the overall effect depends on the relative magnitude of two opposing effects, the ‘convex-cost effect’ and the ‘gambling effect’. We apply the analysis to the Baltic cod and the North Sea herring fisheries, concluding that for risk neutral agents the net effect of environmental uncertainties on the optimal size of these fish stocks is negative, albeit small in absolute value. Under risk aversion, the effect on optimal stock size is positive for sufficiently high coefficients of constant relative risk aversion.

Keywords: fishery economics, environmental uncertainty, constant escapement, risk aversion, prudence

JEL-Classification: Q22, Q57

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Introduction

Environmental uncertainties have important effects on the development of fish stocks (Hilborn and Walters 1992). Accordingly, stochastic fluctuations in environmental variables such as temperature, salinity, or oxygen concentration, have to be taken into account when discussing optimal fishery management. For risk-neutral agents, Reed (1979) shows that optimal management of a fish stock is characterized by a constant escapement policy, i.e. it ensures that a constant proportion of the stock remains in the sea after fishing.¹ Reed (1979) also shows that the optimal constant escapement level in a stochastic environment is equal to, or larger than, the optimal escapement level in a deterministic setting where the unit harvesting cost function fulfills a number of regularity assumptions. Various articles have refined Reed's seminal work by adding multiple uncertainties (Clark and Kirkwood 1986, Sethi et al. 2005), costly capital adjustments (Singh et al. 2006), choice of regulatory instrument (Weitzman 2002), spatial structure of the resource, (Costello and Polasky 2008) and management with environmental prediction (Costello et al. 2001). All these studies assume risk-neutral decision-makers.²

One thing that most of these models have in common is that environmental stochasticity is modeled by an i.i.d. random variable z_t multiplied by the average stock-growth function $f(x_t)$ of the resource stock x_t at time t , i.e. $x_{t+1} = z_t \cdot f(x_t)$.³

The stock-growth function combines the different biological processes of recruitment (young fish entering the harvested stock), survival, and growth in terms of weight. Multiplying the average stock-growth function by one random variable implies that all biological processes are equally affected by environmental fluctua-

¹Reed assumes an objective function that is linear in harvest, which implies that neither the consumer nor the fishermen show risk aversion

²Pindyck (1984) studies the management of renewable resources under uncertainty in continuous time by adding a stochastic differential equation of the Ito type, assuming a downward sloping demand function. This can be interpreted as reflecting risk-aversion of consumers.

³Costello et al. (2001) do not restrict the disturbance to be multiplicative to the stock growth, but still assume that z_t is i.i.d with mean one, which implies that z_t is somehow multiplicatively connected.

tions. From a biological point of view, however, it seems more plausible to assume that the respective processes would be influenced differently by fluctuations in the environmental conditions. In most ecological stock-assessment models of marine fish populations the reproduction process is considered to be more sensitive to environmental fluctuations than the survival of adult fish, which is usually assumed to be constant.⁴ Accordingly, we split the stock-growth function into two functions describing the processes of recruitment and growth on the one hand and of adults surviving natural mortality on the other. The recruitment and growth are assumed to be stochastic, whereas natural mortality is assumed to be fixed.

We examine the effect of uncertainty on the optimal size of a fish stock under both risk neutrality and risk aversion. Whether or not optimal escapement increases with uncertainty is connected with the prudence (Kimball 1990) of the value function. If the value function of the fishery considered exhibits positive prudence, the optimal policy will involve precautionary savings in the natural capital stock and hence higher stock size under uncertainty than in the deterministic case. If the value function exhibits negative prudence, the optimal stock size under uncertainty will be lower than in the deterministic setting. As the value function depends on (i) the biomass growth function, (ii) the profit function, and (iii) the representative fisherman's utility function, all three have an influence on whether optimal escapement increases or decreases with environmental uncertainty.

Considering risk-neutral stakeholders first, we show that the overall effect of uncertainty on the optimal size of a fish stock is ambiguous, depending on the relative magnitude of two opposing effects, the 'convex-cost effect' and the 'gambling effect'. The 'convex-cost effect' reduces optimal escapement under uncertainty over and against the deterministic case. Because harvesting costs are convex in the fish stock, expected harvesting costs are larger when fish stock growth is uncertain than they are at an expected stock level. The 'gambling effect', on the other hand, increases optimal escapement under uncertainty. It comes about because uncer-

⁴The influence of environmental conditions differ for different species. For Baltic cod and North Sea herring see ICES Advice 2010a, 2010b, Books 6 (herring) and 8 (cod).

tainty is multiplicatively connected to stock growth, so the distribution of the next period’s resource rents is positively skewed. This effect induces a risk-neutral fishery manager to ‘bet’ on favorable environmental conditions.

For the case of a risk-averse representative fisherman, we show for a special case that optimal escapement increases with uncertainty if the coefficient of relative risk aversion is large enough.

In quantitative terms, we apply the model to Eastern Baltic cod and North Sea herring fisheries and conclude that under risk neutrality the net effect of environmental uncertainties on the optimal size of these fish stocks is negative, albeit small in absolute value. Under risk aversion we observe a positive effect of uncertainty on optimal stock size for sufficiently high coefficients of constant relative risk aversion.

The paper is structured as follows: In the next section we set up the model and solve the corresponding optimization problem. In Section 2 we consider optimal harvesting under risk neutrality, identifying the convex-cost effect and the gambling effect. The case of a risk-averse representative fisherman is discussed analytically in Section 3. We then apply our model to fisheries for Baltic cod (Section 4) and North Sea herring (Section 5), considering both risk neutrality and risk aversion. Section 6 summarizes and discusses the results.

1 A Fishery Model with Environmental Uncertainty

We consider a simple biomass model with stochastic recruitment in discrete time. The growth of biomass x_t from time step t to $t + 1$ is described by the equation

$$x_{t+1} = g(s_t) + z_t r(s_t), \tag{1}$$

where s_t denotes the escapement, i.e. the biomass that remains in the ecosystem after harvest h_t so that $s_t = x_t - h_t$. The period between t and $t + 1$ is divided into two parts. Harvesting takes place in the first part. In the second, the remaining fish biomass, i.e. the escapement, reproduces and grows in weight. A fraction of

the fish dies by natural causes. The term $g(s)$ represents the survival of adult fish. The reproduction and growth process is represented as the stock-recruitment relationship $r(s)$.

Both functions are differentiable and non-decreasing. The expected recruitment at stock size s_t is described by the strictly concave function $r(s_t)$. Furthermore, the recruitment process is sensitive to environmental uncertainty, represented by the random variable z_t , which is independent and identically distributed over time with an expected value equal to one, $E[z_t] = 1$. The survival of adult fish $g(s_t)$, by contrast, is deterministic. It can be concave or linear in s . In the latter case the natural mortality rate of adult fish is fixed. The assumption of deterministic mortality at a constant rate is common in biological stock assessment models (Hilborn and Walters 1992, ICES 2010a,b). We briefly discuss the case of stochastic mortality in Appendix D.

The price per unit of fish p is constant, i.e. the fishery is small compared to the overall market. We assume a generalized Schaefer production function for the instantaneous harvest rate \tilde{h} in the fishing season, $\tilde{h} = q(\tilde{x}) K_t$. We use $q(\tilde{x})$ to denote the catch per unit of effort, K_t to denote the effort of harvesting fish (which is assumed to be constant throughout the fishing season), and \tilde{x} to denote the current stock size. Accordingly, $\tilde{x} = x_t$ at the beginning of year t 's fishing season and $\tilde{x} = s_t$ at the end (Reed 1979, Clark 1990). Harvesting costs C_t are proportional to effort K_t , with ζ as the costs per unit effort $C_t = \zeta K_t$. Thus we obtain a unit cost function for harvesting fish, $c(\tilde{x}) = \zeta/q(\tilde{x})$. We assume that, in general, unit harvesting costs are weakly decreasing and weakly convex in the stock size, i.e. $c'(\tilde{x}) \leq 0$ and $c''(\tilde{x}) \geq 0$. This means that the catch per unit of effort $q(x)$ is non-decreasing with population abundance. Convexity also implies that the increase of the unit harvesting costs induced by a one-unit decrease in stock is greater for lower stock abundance than for higher stock abundance. A common specification of the harvesting cost function is $c(\tilde{x}) = c \tilde{x}^{-\chi}$ with $\chi > 0$. In that special case $\tilde{x} c(\tilde{x})$ is strictly concave (for $0 < \chi < 1$), constant (for $\chi = 1$), or strictly convex (for $\chi > 1$). For $\chi = 0$, catch per unit effort is independent of

stock abundance, the unit harvesting cost is constant with $C = \zeta$, and $\tilde{x} c(\tilde{x})$ is linear in stock. In empirical terms the most relevant case is $\chi \in (0, 1)$. In a study of 297 fisheries, Harley et al. (2001) find typical values of χ to be between 0.64 and 0.75.

During the harvesting season, each ton of fish caught reduces the stock by one ton. Therefore the aggregate annual profit Π_t is obtained by integrating the flow of profits over the whole fishing season $\Pi_t = \int_{s_t}^{x_t} (p - c(\tilde{x})) d\tilde{x}$. The fishery manager aims to maximize the well-being of the representative fisherman earning his income from fishing profits:⁵

$$\max_{s_t} E \left[\sum_{t=1}^{\infty} \rho^{t-1} u(\Pi_t) d\tilde{x} \right] \quad \text{subject to (1)}. \quad (2)$$

Here the operator E denotes the expectation over the probability distribution of the random process $\{z_t\}$ and $\rho \in (0, 1)$ is the discount factor. Fishermen are typically averse to fluctuations in income. We find this, for example, reflected in the management plans for Baltic cod which contain rules to limit fluctuations in total allowable catches from year to year.⁶ We take this effect into account by assuming that instantaneous utility $u(\Pi_t)$ derived from fishing income is increasing and weakly concave, $u'(\Pi_t) > 0$ and $u''(\Pi_t) \leq 0$.⁷ For a risk-neutral fisherman, the instantaneous utility function is linear, $u(\Pi_t) \equiv \Pi_t$. For a risk-averse fisherman, the instantaneous utility function is strictly concave, $u''(\Pi_t) < 0$.

Using $J(x)$ to denote the value function associated with the stochastic optimization problem (2), the Bellman equation reads⁸

$$J(x) = \max_s \left\{ u \left(\int_s^x (p - c(\tilde{x})) d\tilde{x} \right) + \rho E [J(g(s) + z r(s))] \right\} \quad (3)$$

⁵We follow the convention of the previous literature and chose the escapement as the control variable.

⁶Council Regulation (EC) No 1098/2007 of 18. September 2007.

⁷The assumption of a strictly concave utility function is sensible if fishermen have imperfect access to capital markets. Experimental evidence suggests that a typical value for the coefficient of relative risk aversion is about 0.74 (Andersen et al. 2008).

⁸Because the optimization problem (2) is autonomous, the value function $J(x)$ does not depend on time.

In the following, we use $S^*(x)$ to denote the optimal feedback policy obtained as a solution of (3) for the stochastic case and $\bar{S}^*(x)$ to denote the optimal feedback policy for the corresponding deterministic model, where $z_t \equiv 1$ for all t . The question we are asking in this paper is whether, for a given stock size x , the solution $S^*(x)$ for the stochastic problem is larger than, equal to, or smaller than the solution $\bar{S}^*(x)$ for the deterministic model.

To address this question, we consider the first-order condition for optimal escapement

$$u' \left(\int_s^x (p - c(\tilde{x})) d\tilde{x} \right) (p - c(s)) = \rho E \left[\frac{d}{ds} J(g(s) + z r(s)) \right]. \quad (4)$$

This condition states that for the optimal escapement level s^* at a given stock size x the current marginal profits of the last unit of fish harvested (left-hand side, LHS) equal the discounted expected marginal profits of an additional unit of fish that escapes fishing (right-hand side, RHS). Uncertainty only makes a difference to the RHS of this equation. As the LHS is monotonically increasing in s , the optimal escapement level at a given stock size x will increase with the RHS of (4). Thus, the optimal escapement level will be higher (lower) under uncertainty than with the deterministic setting if the RHS of (4) is higher (lower) when z is stochastic than in the deterministic case $z \equiv 1$. This, in turn, depends on the curvature of the derivative of the value function with respect to the escapement level, $dJ(g(s) + z r(s))/ds$, in z . So the question whether or not optimal escapement increases with uncertainty is connected to the *prudence* (Kimball 1990) of the value function $J(g(s) + z r(s))$.

Prudence describes “the propensity to prepare and forearm oneself in the face of uncertainty, in contrast to ‘risk aversion’, which is how much one dislikes uncertainty and would turn away from uncertainty if possible” (Kimball 1990:54). A positive prudence of the value function thus implies precautionary savings in the natural capital stock and hence higher stock size under uncertainty. Positive prudence is given if $dJ(g(s) + z r(s))/ds$ is convex in the random variable z . The index of absolute prudence is defined by $\frac{d^2}{dz^2} (dJ(g(s) + z r(s))/ds)$. If this index is

positive (negative), we speak of positive (negative) prudence of the value function. Under positive (negative) prudence the optimal stock size under uncertainty will be higher (lower) than in the deterministic setting.

As the value function depends on (i) the biomass growth function, (ii) the profit function, and (iii) the representative fisherman's utility function, all three have an influence on whether optimal escapement increases or decreases with environmental uncertainty. For the detailed analysis of the combined effect we proceed in three stages. In Section 2 we study how optimal harvesting is affected by risk when fishermen are risk-neutral. Section 3 derives analytical results for risk-averse fishermen, but it requires relatively restrictive assumptions on biomass growth function, harvesting technology, and preferences to derive a closed-form expression for the value function. In section 4 and 5 we apply our analysis to the Baltic cod and North Sea herring fisheries.

2 Optimal Harvesting under Risk Neutrality

For the risk-neutral case $u(\Pi_t) \equiv \Pi_t$, both the LHS and the RHS of (4) are independent of the current stock size x . Thus, the solution of this stochastic optimization problem is state-independent (see Appendix A). Optimal feedback policy $S^*(x)$ is the most rapid approach to the constant optimal escapement level s^* ,

$$S^*(x) = s^* \quad \text{if } x > s^* \quad \text{and} \quad S^*(x) = x \quad \text{otherwise.} \quad (5)$$

The optimal escapement level s^* is determined by the following condition (see Appendix B):

$$p - c(s^*) = \rho g'(s^*) \left[p - E_z \left[c(g(s^*) + z_t r(s^*)) \right] \right] + \rho r'(s^*) \left[p - E_z \left[z_t c(g(s^*) + z r(s^*)) \right] \right] \quad (6)$$

This condition states that for the optimal escapement level s^* current marginal profits from the last unit of fish harvested equal the discounted expected marginal profits from an additional unit that escapes fishing. The expected marginal profit

on the RHS of (6) can be divided into two effects. The first term on the RHS represents the expected marginal profits from the additional surviving adults. The second term on the RHS stands for the expected marginal profits from additional recruits.

In the risk-neutral case, the curvature properties of the marginal cost function are essential to determine the prudence of the value function. To compare the optimal escapement level in the stochastic case with the optimal escapement level \bar{s}^* in the deterministic case (i.e., for $z_t \equiv 1$ in Equation (1)), we consider the following equivalent to condition (6) in the deterministic setting:

$$p - c(\bar{s}^*) = \rho g'(\bar{s}^*) \left[p - c \left[g(\bar{s}^*) + r(\bar{s}^*) \right] \right] + \rho r'(\bar{s}^*) \left[p - c \left[g(\bar{s}^*) + r(\bar{s}^*) \right] \right]. \quad (7)$$

We obtain a higher (lower) optimal escapement level when the next period's expected marginal costs are lower (higher) than the marginal costs at the expected next period's stock level (which coincides with the deterministic case as we have $E_z[z] = 1$). We consider the effects for additional surviving adults and for additional recruitment separately. The first term on the RHS of condition (6) in the stochastic case is smaller than the first term on the RHS of condition (7) in the deterministic case. This is due to the convexity of the marginal harvesting cost function. We refer to this effect as the 'convex-cost effect'. The second term on the RHS of condition (6) will be larger than the second term on the RHS of condition (7) if function $\tilde{x} c(\tilde{x})$ is concave. We refer to this effect as the 'gambling effect'.

2.1 Convex-cost effect

If marginal harvesting costs are convex in the fish stock, they will also be convex in the random variable. Expectation $E \left[c(g(s^*) + z_t r(s^*)) \right]$ is over a convex function of the random variable, so expected marginal harvesting costs are greater than the marginal costs at expected stock growth $c(g(s^*) + r(s^*))$ as $E[z] = 1$. The convex marginal cost function implies that the increase in marginal harvesting costs for a stock growth below the mean is greater than the decrease in marginal

harvesting costs for a stock growth above the mean. Accordingly, the expected marginal harvesting costs are greater under uncertainty than in the deterministic case. We refer to this effect, which tends to reduce the optimal escapement level, as the convex-cost effect.

Intuitively, the effect of convex marginal harvesting costs is similar to the effect of risk aversion, so it is optimal to invest less if the asset is risky. Accordingly, it is also intuitive that under uncertainty the convex-cost effect will reduce optimal escapement over and against the deterministic model. More precisely, the convexity of marginal harvesting costs reduces the prudence of the value function. If the convex-cost effect were the only effect present, the prudence of the value function would be unambiguously negative, and the optimal escapement level would decrease with environmental uncertainty.

2.2 Gambling effect

If the function $\tilde{x} c(\tilde{x})$ is convex, the second term on the RHS of condition (6) will be lower than the second term on the RHS of (7). The prudence of the value function would be unambiguously negative, so the optimal escapement level under uncertainty would be unambiguously lower than in the deterministic setting.

As set out earlier, the more relevant case in empirical terms is where $\tilde{x} c(\tilde{x})$ is concave in \tilde{x} . Here the expression $z_t c(g(s^*) + z_t r(s^*))$ is a concave function in the random variable z_t . The expected marginal costs $E\left[z_t c(g(s^*) + z_t r(s^*))\right]$ will then be smaller than the marginal costs at expected stock growth $c(g(s^*) + E[z] r(s^*))$ (which coincides with the deterministic case).

The economic intuition for this effect is as follows: As uncertainty is multiplicatively connected with stock growth, the distribution of next period's resource rents is positively skewed and has a fat tail at high rents. Under favorable environmental conditions, a marginal increase in current escapement will result in a strong marginal increase in the fish stock, producing both a large harvest and low marginal harvesting costs in the next period. Under adverse environmental

conditions, marginal harvesting costs in the next period will be high because of the low fish stock, but this effect is dampened by the fact that the harvest is small. So the expected marginal increase in harvesting costs with a marginal increase in escapement is lower than the marginal increase in harvesting costs under expected stock growth. In other words, a risk-neutral fishery manager will tend to bet on favorable environmental conditions. This is why we call this effect the gambling effect.

The gambling effect tends to increase the prudence of the value function, i.e. to increase the optimal escapement level under environmental uncertainty.⁹

Since the convex-cost effect and the gambling effect work in opposite directions, the overall result is ambiguous. The optimal escapement level could be either higher or lower than in the deterministic case.¹⁰

2.3 A special case: when survival is proportional to recruitment

In our model, a special case arises if survival is proportional to recruitment, i.e. if there exists some $\kappa \in [0, 1)$ such that $(1 - \kappa)g(s) = \kappa r(s)$. In this case, biomass growth (equation 1) can be written as

$$x_{t+1} = \tilde{z}_t f(s_t), \tag{8}$$

where $\tilde{z} = \kappa + (1 - \kappa)z$ is a random variable with mean 1 and $f(s) \equiv r(s)/(1 - \kappa)$ is the expected biomass growth function. This special case deserves attention, as the model for it is equivalent to the model studied by Reed (1979). In the latter

⁹It may appear contradictory that the ‘gambling effect’ leads to a higher degree of prudence. However, the term *prudence* has been coined because of its effect – a higher degree of prudence induces higher precautionary savings – and not because of a particular motivation why an agent saves more under uncertainty.

¹⁰Under constant unit harvesting costs both the gambling and the convex-cost effect vanish and the optimal escapement level in the stochastic and deterministic model are the same.

case the optimality condition (6) simplifies to

$$p - c(s^*) = \rho f'(s^*) \left(p - E_{\tilde{z}} \left[z c(\tilde{z} f(s^*)) \right] \right). \quad (9)$$

If the function $\tilde{x} c(\tilde{x})$ is concave in \tilde{x} , the optimal escapement level in the stochastic model will be unambiguously higher than in the deterministic case.¹¹ In other words the gambling effect will outweighs the convex-cost effect.

If we further specify the unit cost function $c(x) = c x^{-\chi}$ with $\chi \in (0, 1)$ and assume a log-normal distribution of environmental stochasticity \tilde{z} with mean $\mu_{\tilde{z}} = 1$ and standard deviation $\sigma_{\tilde{z}}$, condition (9) can be written as follows (see Appendix C):

$$p - c(s^*) = \rho f'(s^*) \left(p - \frac{c f(s^*)^{-\chi}}{(1 + \sigma_{\tilde{z}}^2)^{\frac{\chi(1-\chi)}{2}}} \right), \quad (10)$$

The left hand-side of this equation increases with the degree of uncertainty, as measured by the variance $\sigma_{\tilde{z}}^2$. Accordingly, the optimal escapement level increases monotonically with uncertainty. In quantitative terms, the influence of uncertainty on the optimal escapement level will typically be small. It is maximal for $\chi = 1/2$, as then the exponent of the factor $(1 + \sigma_{\tilde{z}}^2)^{\chi(1-\chi)/2}$ on the RHS of (10) reaches its maximum for all values of $\chi \in (0, 1)$. But even in this case and for an unrealistically high degree of uncertainty $\sigma_{\tilde{z}}^2 = 1$, this factor changes the RHS of (10) by less than ten percent, as $(1 + \sigma_{\tilde{z}}^2)^{\chi(1-\chi)/2} = 2^{1/8} < 1.10$.

3 Optimal Harvesting under Risk Aversion

In the case of risk aversion, it is in general not possible to solve the Bellman equation (3) analytically. For special cases an analytical solution is however feasible.¹²

¹¹Reed's (1979) intuitive explanation for a higher optimal escapement level is that "the marginal average annual harvesting cost in the stochastic model resulting from an increase in the escapement level [...] is, because of the averaging process, less than the corresponding marginal cost in the deterministic model."

¹²To our knowledge, no analytically solvable model has been available for the discrete-time model so far. For a similar problem in continuous time, Pindyck (1984) provides three examples of analytically solvable models.

To study the case of a risk-averse representative fisherman analytically, we thus have to further specify the model.

First, we neglect harvesting costs in this section, i.e. we assume $c(\tilde{x}) \equiv 0$. This not only simplifies the analysis, it also enables us to better isolate the effect of risk aversion. The point is that in the absence of harvesting costs, both the convex-cost effect and the gambling effect vanish, and optimal escapement for the risk-neutral case would be independent of uncertainty.

Second, we focus on the case where survival is proportional to recruitment and the biomass growth function is given by (8). We furthermore assume that the biomass growth function $f(s)$ has the functional form

$$f(s) = (\alpha s^{1-\phi} + \alpha \beta^{1-\phi})^{\frac{1}{1-\phi}} \quad (11)$$

with positive constants α , β , and ϕ . A special case of this biomass growth function is the Beverton-Holt function $f(s) = (s/\alpha)/(1 + (s/\beta))$ obtained by setting $\phi = 2$.

Third, we assume an instantaneous utility function with constant relative risk aversion $\vartheta > 0$,

$$u(\Pi(x, s)) = \frac{\nu}{1-\vartheta} (x-s)^{1-\vartheta}, \quad (12)$$

with $\nu > 0$. This model is analytically solvable for the special case $\phi = \vartheta$. In Appendix E we show that the value function is

$$J(x) = \frac{\psi_1}{1-\vartheta} x^{1-\vartheta} + \psi_2 \quad (13)$$

with some constants $\psi_1 > 0$ and ψ_2 , and that the optimal escapement rule is

$$s^* = (\rho \alpha E[z^{1-\vartheta}])^{\frac{1}{\vartheta}} x. \quad (14)$$

It is obvious that if $\vartheta < 1$ ($\vartheta > 1$), optimal escapement will be lower (higher), the higher the uncertainty is. $\vartheta < 1$ means not only that risk aversion is relatively low but also that the curvature of the biomass growth function is relatively high.¹³

¹³If we again assume that z is log-normally distributed with variance σ_z^2 , we obtain $(E[z^{1-\vartheta}])^{1/\vartheta} = (1 + \sigma_z^2)^{(1-\vartheta)/2}$ (see appendix C).

We can again connect this result to the prudence of the value function $J(\tilde{z} f(s))$. In this case, the function inside the expectation operator on the RHS of (4) is $dJ(\tilde{z} f(s))/ds = \psi_1 z^{1-\vartheta} \alpha s^{1-\vartheta}$. It is concave (convex) in ϑ if $\vartheta < 1$ ($\vartheta > 1$). Thus, a value function that exhibits negative (positive) prudence will give rise to a lower (higher) optimal escapement for $\vartheta < 1$ ($\vartheta > 1$).

4 Quantitative Example I: Baltic Cod Fishery

Our first quantitative example is the Baltic cod fishery. The water in the Baltic Sea is brackish, making it a marginal area for cod. The fish population depends on fluctuating fresh water inflows from the North Sea to increase the salinity level to a degree where their eggs can hatch (Röckmann et al. 2007). Accordingly, the recruitment process for Baltic cod is highly uncertain and represents a useful example for the stochastic recruitment model.

To estimate the biological growth function we use stock assessment data (years 1966-2009) from the International Council of the Exploration of the Sea (ICES 2011). We combine the data for total stock biomass in year t , X_t , total harvest H_t (as the sum of official landings and discards) and natural mortality (assumed to be fixed at $M = 0.2$, as in the ICES stock assessments) to obtain the escapement S_t and the recruitment biomass R_t as follows

$$\begin{aligned} S_t &= X_t - H_t, \\ R_t &= X_{t+1} - e^{-0.2} S_t. \end{aligned}$$

The recruitment variable R_t thus encompasses both the reproduction process and growth in weight. It is calculated as the total stock biomass at the beginning of period $t + 1$ minus the fraction of period t 's escapement that survives natural mortality. We assume that recruitment follows a stochastic Beverton-Holt (1957) stock-recruitment function $r(s_t) = z_t \alpha_1 s_t / (1 + \alpha_2 s_t)$.¹⁴ Using the Levenberg-

¹⁴We also estimated the more general growth function of $r(s_t) = (\alpha s_t^{1-\phi} + \alpha \beta^{1-\phi})^{\frac{1}{1-\phi}}$, but found the parameters to be not significant.

Marquardt algorithm for nonlinear least squares, we estimated the equation

$$\ln(R_t) = \ln\left(\frac{\alpha_1 S_t}{1 + \alpha_2 S_t}\right) + \varepsilon_t, \quad (15)$$

assuming that ε_t is an independent and identically normally distributed random variable with zero mean.¹⁵ We obtain estimates $\hat{\alpha}_1 = 1.189$ with a standard error of 0.111, $\hat{\alpha}_2 = 1.525$ million tons with a standard error of 0.496 million tons, and an estimate $\hat{\sigma}^2 = 0.083$ million tons for the standard deviation of $z_t = \exp(\varepsilon_t)$. Because of the logarithmic specification of (15), estimate $\hat{\alpha}_1$ is biased. For our numerical computations, we use the adjusted value $\alpha_1 = \hat{\alpha}_1 \exp(-0.5 \hat{\sigma}^2) = 1.140$.

To estimate the parameters of the harvesting function, we specify the cost function $C = \zeta K_t$ and $q(\tilde{x}) = q_0 x^\chi$. With this specification, total fishing effort in year t is $K_t = \int_{s_t}^{x_t} q(\tilde{x})^{-1} d(\tilde{x}) = \frac{1}{q_0(1-\chi)} [x^{1-\chi} - s^{1-\chi}]$ (Clark 1990). We use data on effort as days at sea for the Danish fleet from (Fiskeriregnskabsstatistik 2007, Fiskeridirektoratet 2007) and (ICES 2009) data for total biomass and escapement. Using the Levenberg-Marquardt algorithm for nonlinear least squares we obtain $q_0 = 5.162$ tons per days at sea (standard error 2.173), and $\chi = 0.953$ (standard error 0.213). For prices and unit effort cost ζ , we use the estimate from Kronbak (2002; 2005) and Quaas et al. (2010). Normalizing the price of a million tons of harvest to unity, we obtain a unit effort cost parameter of $\zeta = 0.554$, measured in billions of Euros at million days at sea. For the unit harvesting cost parameter we thus have $\zeta/q_0 = 0.107$ Euros/kg.

In sum, the functional specifications we use are

$$\begin{aligned} g(s_t) &= e^{-0.2 s_t} \\ r(s_t) &= \frac{1.140 s_t}{1 + 1.525 s_t} \\ z_t &\propto \text{LOGN}(1, 0.083) \\ p - c(\tilde{x}) &= 1 - 0.107 \tilde{x}^{-0.953} \\ \rho &= \frac{1}{1 + 0.05} \end{aligned}$$

¹⁵A Durbin-Watson test shows no autocorrelation in the error terms ($DW = 1.718$, $p = 0.312$).

Our first step in the quantitative analysis for Baltic cod is to consider the optimal escapement levels for a risk-neutral representative fisherman. To determine the optimal escapement levels in the deterministic and stochastic recruitment models, we solve conditions (6) and (7) using these specifications numerically. For our sensitivity analysis, we use random samples of 1000 sets of parameter values for α_1 , α_2 , q_0 and ζ , assuming that the parameter values are independently normally distributed with means and standard deviations as obtained from the estimations (or variance-covariance matrix from the estimation for α_1 and α_2). For each parameter set, we compute the optimal escapement and determine the standard deviation of the sample of optimal escapement levels thus obtained.

The optimal escapement level for the deterministic model (where $z \equiv 1$) is $\bar{s}^* = 0.904$ million tons, with a standard deviation of 0.257 million tons. For the stochastic model we obtain $s^* = 0.902$ million tons as the optimal escapement, with a standard deviation of 0.255 million tons. Thus we have a slightly lower optimal escapement level in the stochastic model than its deterministic counterpart, but the difference of 1 619 tons (with a standard deviation of 657 tons) is small. This indicates that while model uncertainty is substantial, it is not so large as to make the quantitative results completely unreliable.

Next, we analyze how risk aversion influences the results. For this purpose, we assume an instantaneous utility function with constant relative risk aversion $u(\Pi_t) = \Pi_t^{1-\vartheta}/(1-\vartheta)$ and use the same biomass growth function, marginal cost function, and discount rate as before. We solve the stochastic optimization problem (2) numerically for different risk-aversion coefficients ϑ by numerically computing the value function $J(x)$. To do so, we use the collocation method (Miranda and Fackler 2002), where the value function $J(x)$ is approximated by a finite linear combination of Chebychev polynomials.¹⁶

The results are shown in Figure 1. The upper panel shows the optimal feedback

¹⁶For cod (herring), we use 101 (212) collocation nodes on the interval $x \in [0.1, 5]$ million tons ($x \in [0.1, 8]$ million tons). The optimization routines were implemented in Matlab. All program codes will be made available as online supporting material.

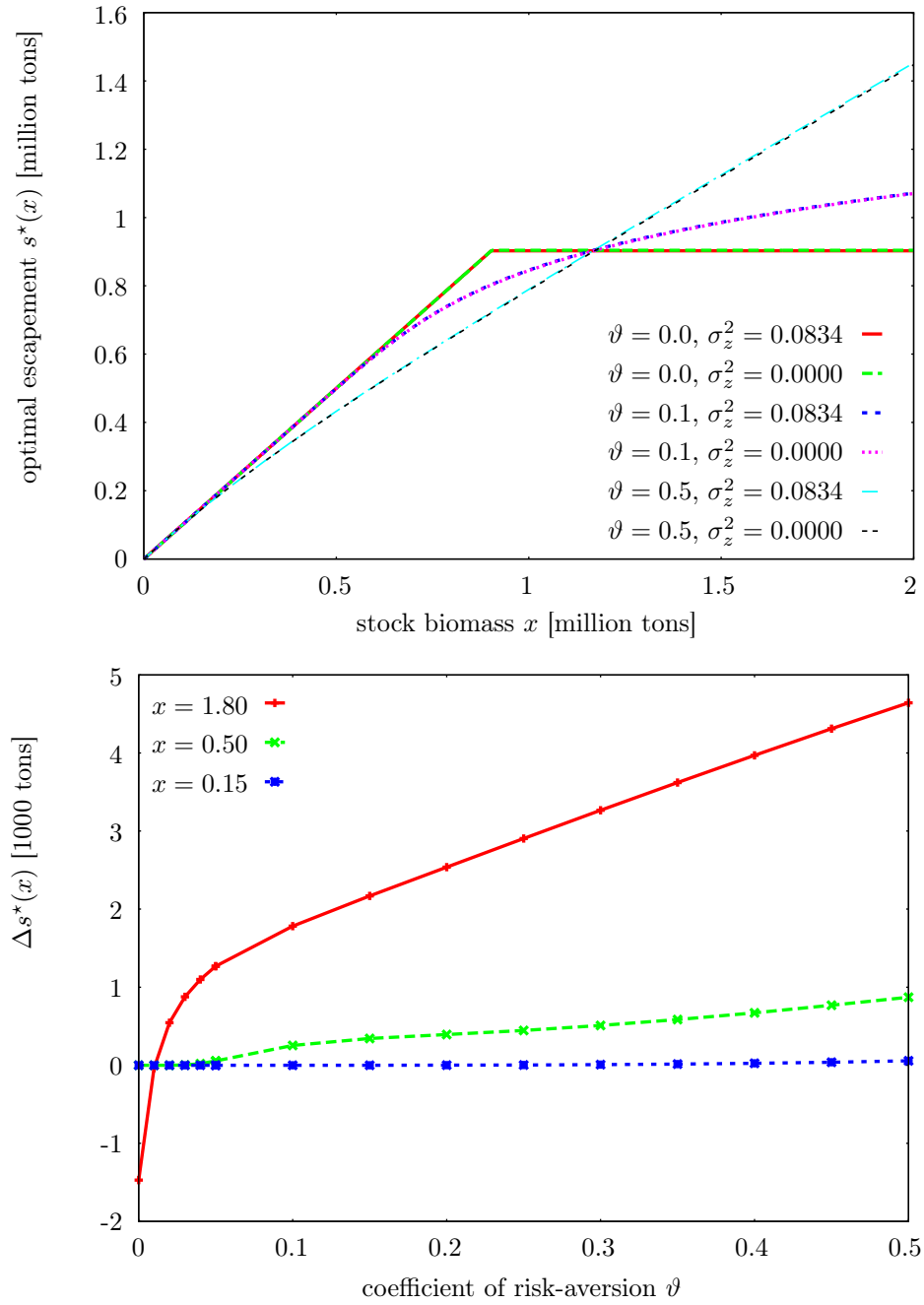


Figure 1: Optimal escapement for Eastern Baltic cod as a function of the representative fisherman's coefficient of risk aversion ϑ . Note that the scale on the y-axis in the upper panel is in millions of tons, while it is in thousands of tons in the lower panel.

policies $S^*(x)$ under uncertainty ($\sigma_z^2 = 0.0834$) and $\bar{S}^*(x)$ in the deterministic case for three different coefficients of risk aversion: the risk-neutral case $\vartheta = 0$, slight risk aversion $\vartheta = 0.1$, and stronger risk aversion $\vartheta = 0.5$. For the risk-neutral case, the optimal policy is the most rapid approach to constant escapement (cf. section 2). The higher the risk aversion, the smoother the optimal policy becomes: escapement is relatively lower (harvest is higher) at relatively low stock sizes, and relatively higher (harvest is lower) at higher stock sizes.

For all three coefficients of risk aversion, there is hardly any difference between the optimal policies under uncertainty and in the deterministic setting. The lower panel in Figure 1 shows the difference $S^*(x) - \bar{S}^*(x)$ for three different stock levels, $x \in \{0.15, 0.50, 1.8\}$ million tons. Note that the scale of the y axis in the lower panel is in thousands of tons, while in the upper panel it is in millions of tons. This shows that the difference is well below 1 percent of the optimal escapement. Although the overall effect is small, the effect of increasing risk aversion is unambiguous. The higher the coefficient of risk aversion is, the higher is the difference in optimal escapement under uncertainty and in the deterministic case. The two lower stock sizes considered ($x = 0.15$ and $x = 0.50$ million tons) are smaller than the optimal escapement s^* in the risk-neutral case. For these stock sizes, the optimal escapement for $\vartheta \rightarrow 0$ is the same with and without uncertainty, as it simply equals the current stock size. The higher stock size $x = 1.8$ million tons is above s^* . In this case, the optimal escapement for a risk-neutral representative fisherman is lower under uncertainty than in the deterministic case (see above). With increasing risk aversion, the difference also becomes positive for this stock size .

5 North Sea Herring Fishery

Our second case study is the North Sea herring fishery. Here we use the same functional specifications as for the Baltic cod fishery. For North Sea herring, we use the price and cost function from Nostbakken (2008), where $p = 2.465$

NOK/ kg, $\zeta = 1,189,565$ NOK/per vessel-year and a catchability per vessel-year of $q_0 = 0.0011$. We again normalize the price to unity and obtain $\zeta/(p*q_0) = 0.439$ Euros/kg and $\chi = 1$ as parameters of the cost function.

To estimate the parameters of the biological growth function, we use ICES (1998; 2007) data for the period 1947-2005 to calculate the escapement S_t as the product of the total biomass X_t and e^{-F} , where F is the mean fishing mortality rate for age classes from 2 to 6. We again assume a deterministic natural mortality with a rate of $M = 0.16$ (as in the ICES stock assessments for herring) and a Beverton-Holt function for the stock-recruitment relationship. Using the same model (15) and regression method as for cod, we obtain estimates $\hat{\alpha}_1 = 2.048$ (standard error 0.266), $\hat{\alpha}_2 = 0.956$ million tons (standard error 0.204 million tons), and $\hat{\sigma}^2 = 0.104$ million tons for the standard deviation of $z_t = \exp(\varepsilon_t)$. Again, we use the adjusted value $\alpha_1 = \hat{\alpha}_1 \exp(-0.5 \hat{\sigma}^2) = 1.9445$ for our numerical analysis.¹⁷

For the risk-neutral case we compute an optimal escapement level $s^* = 2.769$ million tons (with a standard deviation of 0.302 million tons) in the stochastic model. In the deterministic model the optimal escapement level is $\bar{s}^* = 2.780$ million tons. Thus we again observe a slightly lower optimal escapement level in the stochastic case. The difference is larger than with the Baltic cod fishery but at 10356 tons (with a standard deviation of 4784 tons) still quite small.

In Fig.2 we show the optimal policies for risk-averse fishermen. The results are similar to those obtained for Baltic cod. The differences in optimal escapements between the stochastic and deterministic cases are small in absolute value. The unambiguous effect of risk aversion is that difference increases and, for sufficiently high degrees of risk aversion, optimal escapement is higher under uncertainty than in the deterministic case.

¹⁷ The Durbin-Watson test revealed autocorrelation in the error term ($DW = 1.014$, $p = 3.647 * 10^{-5}$). As Nostbakken (2008) states, “[s]ome problems of autocorrelation are [...] inevitable when using a simple surplus growth model to explain the complex dynamics of the fish stock”. Considering an autoregressive model for the error term means that another stock variable has to be included in the model. This would greatly increase the complexity of the stochastic optimization problem, which is beyond the scope of the present paper.

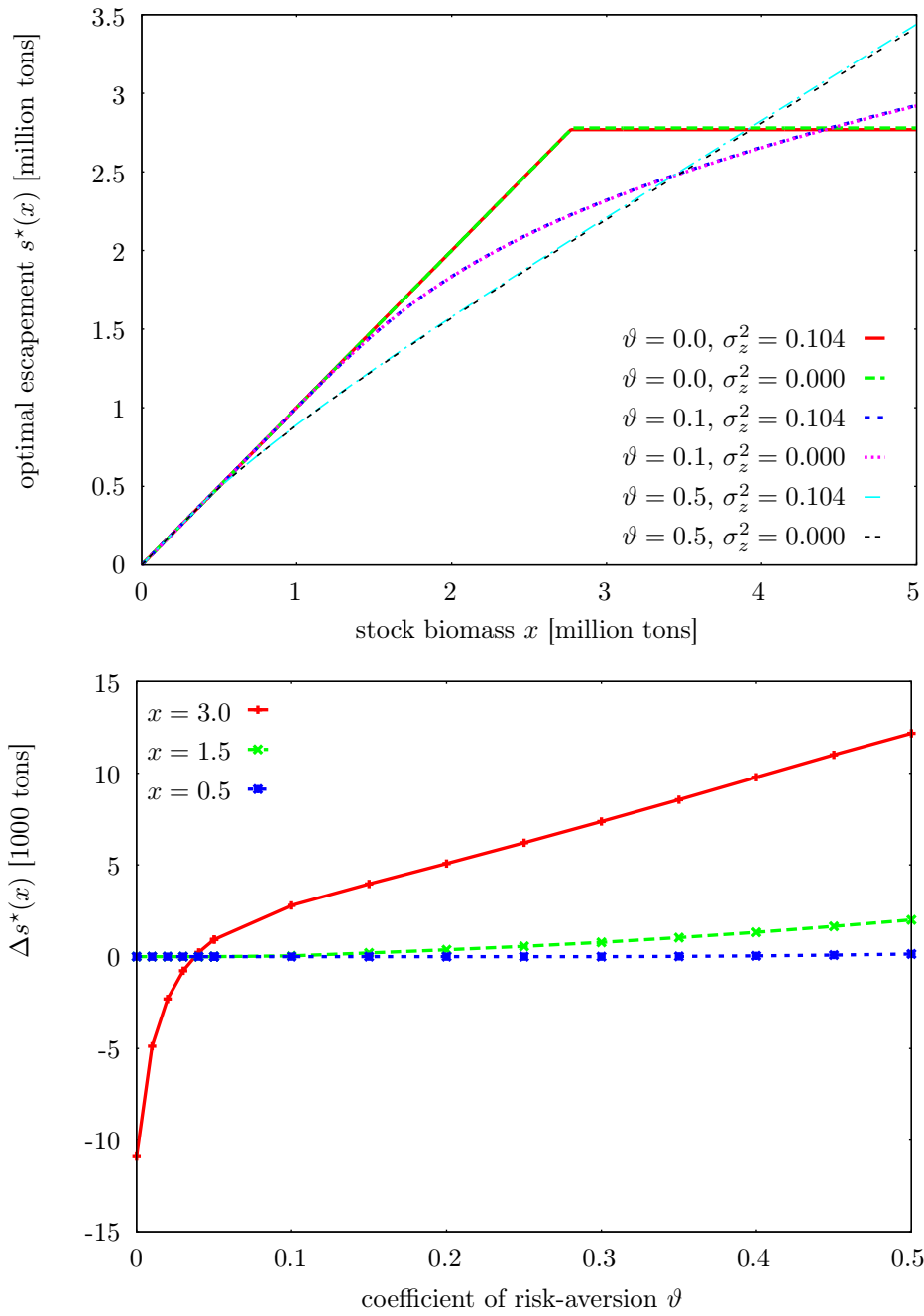


Figure 2: Optimal escapement for North Sea herring as a function of the representative fisherman's coefficient of risk aversion ϑ . Note that the scale on the y-axis in the upper panel is in millions of tons, while it is in thousands of tons in the lower panel.

6 Discussion and Conclusion

In this paper we studied the effects of environmental uncertainties on optimal fishery management for both risk-neutral and risk-averse fishermen. To account for natural mortality and recruitment, we split the stock growth function of the fish stock into two processes. Following the biological approach taken in stock assessment models, we assume that natural mortality is fixed at a given value. The recruitment process, by contrast, depends on stochastically fluctuating environmental conditions.

We have demonstrated that the optimal escapement level can be higher or lower than in the deterministic setting, depending on the prudence of the value function. This in turn depends on (i) the biomass growth function, (ii) the profit function and (iii) the representative fisherman's utility function. Positive prudence gives rise to higher optimal escapement, whereas negative prudence results in a lower optimal escapement level.

For risk-neutral fisherman we showed that the question whether or not the optimal escapement increases with uncertainty is influenced by two counteracting cost effects: the convex-cost effect and the gambling effect. The convex-cost effect results from higher expected marginal costs due to the convexity of the cost function and tends to reduce optimal escapement. Intuitively, the convex-cost effect means that optimal investment is smaller when the asset is risky. The gambling effect results from lower expected marginal costs under uncertainty because the harvestable biomass increases more strongly under favorable environmental conditions than under adverse environmental conditions. The gambling effect thus tends to increase optimal escapement. The finding that the effect of uncertainty on the optimal size of the fish stock is ambiguous under risk neutrality is in contrast to Reed's (1979) unambiguous result that the optimal constant escapement level in a stochastic environment is equal to, or larger than, the optimal escapement level in a deterministic setting. This is because we have allowed that the processes of recruitment and adult survival are affected differently by environmental uncertain-

ties. In the paper we have considered the case where recruitment is uncertain, but survival is deterministic. In Appendix D we show that the effect of uncertainty is ambiguous also in the case of stochastic survival. Under risk aversion, the effect of uncertainty on optimal escapement is still ambiguous, depending on the stock growth function parameter and the coefficient of constant relative risk aversion.

To quantify the effect of uncertainty both under risk neutrality and risk aversion, we applied the model to the Baltic cod and the North Sea herring fisheries. Under risk neutrality we observed in both fisheries lower optimal escapement in the stochastic environment than in the deterministic setting, but the difference is small in absolute value. In the setting with risk-averse fishermen we found higher optimal escapement levels for sufficiently high coefficients of constant relative risk aversion. Again, the difference is very small, and well below one percent of optimal escapement.

This finding is in line with previous results of Sethi et al. (2005) who analyze the effect of multiple uncertainties on optimal fishery management. Their simulations show that stock growth uncertainty has only minor effects on the optimal fishery management. Our paper completes their findings: By introducing the two cost-effects and referring to the notion of prudence, we provide a deeper understanding and an intuitive explanation of the influence of environmental uncertainties on the optimal fishery management. We extend the analysis to the case of risk aversion, both analytically and numerically. Furthermore by applying our model to two real fisheries, incorporating the estimated variance in stock growth and the estimated cost function, we provide valid results for fishery management.

Our quantitative results show that the optimal feedback policy is not very strongly affected by environmental uncertainties. Our results suggest that even if fluctuations in environmental conditions would increase, for example due to climate change, there is little need to adapt fishery management recommendations. One should keep in mind, however, that other forms of uncertainty may have a much stronger effect, including measurement uncertainty with regard to the size of the fish stock (Sethi et al. 2005), or the possibility of regime shifts (Polasky et al.

2011, de Zeeuw and Zemel 2012).

Appendix

A Dynamic Programming and Constant Escapement Policy

We consider the problem for a finite time horizon T . The result for an infinite time horizon is then obtained by letting $T \rightarrow \infty$. The risk neutral fishery manager faces the following maximization problem:

$$\max_{s_t} E \left[\sum_{t=1}^T \rho^{t-1} \int_{x_t - h_t}^{x_t} p - c(\tilde{x}) d\tilde{x} \right] \quad (16)$$

$$\text{s.t. } x_{t+1} = g(s_t) + z_t r(s_t). \quad (17)$$

By letting $\Pi(x_t, s_t) = \pi(x_t) - \pi(s_t) = \int_{s_t}^{x_t} \pi'(v) dv$ and $\pi'(v) = p - c(v)$ equation (16) can be also expressed as

$$\max_{s_t} E \left[\sum_{t=1}^T \rho^{t-1} (\pi(x_t) - \pi(s_t)) \right].$$

To demonstrate that the optimal management approach is of the constant escapement type analogous to Reed (1979) we solve the Bellman equation by backward induction:

$$J_n(x_{T-(n-1)}) = \max_{s_{T-(n-1)}} \left\{ (\pi(x_{T-(n-1)}) - \pi(s_{T-(n-1)})) + \rho E[J_{n-1}(x_{T-n})] \right\}, \quad (18)$$

where the operator E denotes the expectation over the probability distribution of the random variable z_t . First we solve the problem for the last period T :

$$J_1(x_T) = \max_{s_T} [\pi(x_T) - \pi(s_\infty)],$$

where s_T is assumed to be the escapement level corresponding to the open-access fishery s_∞ . Now we consider the problem for the penultimate period:

$$J_2(x_{T-1}) = \max_{s_{T-1}} \left\{ (\pi(x_{T-1}) - \pi(s_{T-1})) + \rho E[\pi(x_T) - \pi(s_\infty)] \right\},$$

where s_∞ is a constant and $x_T = g(s_{T-1}) + z_t r(s_{T-1})$, such that the previous equation can be written as

$$J_2(x_{T-1}) = \max_{s_{T-1}} \left\{ (\pi(x_{T-1}) - \pi(s_{T-1})) + \rho E [\pi(g(s_{T-1}) + z_t r(s_{T-1}))] \right\} + \text{const.} \quad (19)$$

Under the assumptions on the curvature properties of $g(\cdot)$, $r(\cdot)$ and $c(\cdot)$, this problem has a unique maximum at an escapement level which we denote by s^* . This escapement level is optimal if the stock at the beginning of the period (x_t) is greater than s^* . The optimal policy is a most rapid approach strategy to s^* . This can be validated by inserting s^* in $J_2(x_{T-1})$ and substituting the result in $J_3(x_{T-2})$:

$$J_2(x_{T-1}) = (\pi(x_{T-1}) - \pi(s^*)) + \rho E [\pi(g(s^*) + z_t r(s^*))] + \text{const.}$$

Since s^* is constant, in particular note, that s^* is independent of stock, x_t , the function can be rewritten as

$$J_2(x_{T-1}) = \pi(x_{T-1}) + \text{const.}$$

Now we consider $J_3(x_{T-2})$:

$$J_3(x_{T-2}) = \max_{s_{T-2}} \left\{ (\pi(x_{T-2}) - \pi(s_{T-2})) + \rho E [J_2(x_{T-1})] \right\}. \quad (20)$$

Inserting $J_2(x_{T-1}) = \pi(x_{T-1}) + \text{const}$ yields

$$J_3(x_{T-2}) = \max_{s_{T-2}} \left\{ (\pi(x_{T-2}) - \pi(s_{T-2})) + \rho E [\pi(g(s_{T-2}) + z_t r(s_{T-2}))] \right\} + \text{const.} \quad (21)$$

Since $J_3(x_{T-2})$ is equivalent to $J_2(x_{T-1})$ in (19) except for the constant the constant escapement strategy s^* is also valid for the period $T - 2$. By complete induction the same holds for all periods.

B Optimal Escapement Level

We now consider the optimal escapement level in the stochastic growth model. By differentiating equation (18) with respect to $s_{T-(n-1)}$ we get the following condition:

$$\pi'(s^*) = \rho E \left[\pi'(g(s^*) + z_t r(s^*)) (g'(s^*) + z_t r'(s^*)) \right].$$

Substituting $p - c(v)$ for $\pi'(v)$ and rearranging we get

$$p - c(s^*) = \rho g'(s^*) \left(p - E \left[c(g(s^*) + z_t r(s^*)) \right] \right) + \rho r'(s^*) \left(p - E \left[z_t c(g(s^*) + z r(s^*)) \right] \right). \quad (22)$$

C Increasing uncertainty when survival is proportional to recruitment

Inserting the cost function $c(\tilde{x}) = \zeta \tilde{x}^{-\chi}$ in equation (9) and rearranging we get

$$p - c(s^*) = \rho f'(s^*) \left(p - \frac{\zeta}{f(s^*)^\chi} E_{\tilde{z}}[\tilde{z}^{1-\chi}] \right).$$

With \tilde{z} as a lognormally-distributed random variable the expectation can be calculated as

$$E_{\tilde{z}}[\tilde{z}^{1-\chi}] = \int_0^\infty \tilde{z}^{1-\chi} \frac{1}{\tilde{z} \sqrt{2\pi s_t^2}} \exp\left(-\frac{(\ln z - m_{\tilde{z}})^2}{2s_t^2}\right) dz.$$

With $\mu_{\tilde{z}} = 1$, the parameters are $m_{\tilde{z}} = -\frac{1}{2} \ln(1 + \sigma_{\tilde{z}}^2)$ and $s_{\tilde{z}}^2 = \ln(1 + \sigma_{\tilde{z}}^2)$.

Substituting $\ln(z) = q$ we get

$$E_{\tilde{z}}[\tilde{z}^{1-\chi}] = \int_0^\infty \exp((1-\chi)q) \frac{1}{\sqrt{2\pi s_t^2}} \exp\left(-\frac{(q - m_{\tilde{z}})^2}{2s_t^2}\right) dq,$$

which yields

$$E_{\tilde{z}}[\tilde{z}^{1-\chi}] = \left(1 + \sigma_{\tilde{z}}^2\right)^{\frac{\chi(1-\chi)}{2}}.$$

For $\chi \in (0, 1)$ the expectation decreases with increasing variance σ^2 . This results in lower expected costs and higher expected profits and gives thus an incentive to choose a higher escapement level.

D Optimal escapement with both mortality and recruitment stochastic

In this appendix we briefly consider the case where both processes, survival and recruitment, are stochastic, i.e. we replace (1) by

$$x_{t+1} = w_t g(s_t) + z_t r(s_t), \quad (23)$$

with two i.i.d. random variables w_t and z_t . The condition for the optimal escapement level (6) under risk-neutrality then generalizes to

$$p - c(s^*) = \rho g'(s^*) \left[p - E_{w,z} \left[w_t c(w_t g(s^*) + z_t r(s^*)) \right] \right] + \rho r'(s^*) \left[p - E_{w,z} \left[z_t c(w_t g(s^*) + z_t r(s^*)) \right] \right]. \quad (24)$$

If w_t and z_t are perfectly correlated, this model is equivalent to Reed's (1979) model, and the optimal escapement level under uncertainty is unambiguously larger than in the deterministic case. If w_t and z_t are not perfectly correlated, the effect of uncertainty on the optimal escapement level is ambiguous. This holds in particular for the case where w_t and z_t are independent. To show this, we consider the example of the Baltic Cod fishery considered in Section 4. The only modification is that we assume that the two random variables $z_t \propto \text{LOGN}(1, \sigma_z^2)$ and $w_t \propto \text{LOGN}(1, \sigma_w^2)$ are independently distributed with $\sigma_w^2 \geq 0$. For $\sigma_z^2 = \sigma_w^2 = 0$, we obtain $\bar{s}^* = 0.904$ million tons (see Section 4). For the example considered here, we set $\sigma_z^2 = 0.5$, slightly higher than the empirical value. For $\sigma_w = 0.1$, we get $s^* = 0.901 < \bar{s}^*$. For $\sigma_w = 0.5$, we get $s^* = 0.911 > \bar{s}^*$. Thus, the effect of uncertainty is ambiguous.

E Optimal escapement with risk aversion

Using $c(\tilde{x}) \equiv 0$, the biomass growth equation (8) with the specification (11), $u(\Pi) = \nu \Pi^{1-\vartheta}/(1-\vartheta)$, and $\phi = \vartheta$ in (4), the first-order condition for optimal escapement becomes

$$\frac{\nu p^{1-\vartheta}}{(x-s)^\vartheta} = \rho E \left[\frac{d}{ds} J \left(z \left(\alpha s^{1-\vartheta} + \alpha \beta^{1-\vartheta} \right)^{\frac{1}{1-\vartheta}} \right) \right] \quad (25)$$

Guessing $s = \delta x$ with some $\delta > 0$ and (13) for the value function, condition (25) becomes

$$\frac{\nu p^{1-\vartheta}}{((1-\delta)x)^{\vartheta}} = \rho \psi_1 E[z^{1-\vartheta}] \alpha (\delta x)^{-\vartheta} \quad (26)$$

$$\Leftrightarrow \nu p^{1-\vartheta} \left(\frac{\delta}{1-\delta}\right)^{\vartheta} = \rho \alpha E[z^{1-\vartheta}] \psi_1 \quad (27)$$

The Bellman-equation reads

$$J(x) = \frac{\nu p^{1-\vartheta}}{1-\vartheta} ((1-\delta)x)^{1-\vartheta} + \rho E[J(zf(\delta x))]$$

Using the guess (13) again, we obtain

$$\frac{\psi_1}{1-\vartheta} x^{1-\vartheta} + \psi_2 = \frac{\nu p^{1-\vartheta}}{1-\vartheta} ((1-\delta)x)^{1-\vartheta} + \rho E\left[\frac{\psi_1}{1-\vartheta} z^{1-\vartheta} (\alpha (\delta x)^{1-\vartheta} + \alpha \beta^{1-\vartheta}) + \psi_2\right]$$

$$\psi_1 = \nu p^{1-\vartheta} (1-\delta)^{1-\vartheta} + \rho E[z^{1-\vartheta}] \alpha \delta^{1-\vartheta} \psi_1 \quad (28)$$

$$\psi_2 = \frac{\rho}{1-\rho} E[z^{1-\vartheta}] \alpha \beta^{1-\vartheta} \psi_1 \quad (29)$$

Using (28) in (27), we obtain (14).

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Optimal harvest-control rules for stochastic fish stocks when stakeholders are risk-averse*

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Abstract.

We analyze how the optimal harvest-control rule (HCR) for a fishery depends on the degrees of risk aversion of fishermen and consumers of fish. We derive analytical solutions for a class of specific discrete-time models, and numerical results in an application to the Eastern Baltic cod fishery. With a higher degree of risk aversion of stakeholders, the optimal HCR becomes flatter and shifts more uncertainty from harvest to the stock; mean and coefficient of variation (CV) of harvest will decrease, while the CV of the resource stock will increase. The effect of risk aversion on the mean resource stock is ambiguous.

Keywords: fishery economics; Baltic cod; European fishery management; uncertainty; stochastic programming; risk aversion

JEL-Classification: Q22, Q57

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1 Introduction

Growth and reproduction of a fish stock are strongly influenced by variable environmental conditions like oxygen concentration, salinity and temperature such that stock biomass and harvest quantities are hard to predict. This is of particular relevance for risk averse fishermen who prefer smoothed intertemporal income and for risk averse consumers who want a steady supply of fish. We analyze how the optimal harvest-control rule (HCR) for a fishery depends on the degrees of risk-aversion of fishermen and consumers of fish. Under uncertainty, an optimal management plan has to be specified in form of a harvest-control rule, or feedback policy, that specifies the harvest quantity as a function of the current stock size. This is also the approach taken for fisheries management plans (Froese et al. 2011).

In this paper we determine the optimal HCR for different degrees of risk aversion among the stakeholders and apply our analysis to the Eastern Baltic cod fishery. There is a broad literature in resource economics on optimal fishery management under uncertain stock growth. However, most studies assume risk neutral fishermen and consumers. Reed (1979) shows that for risk neutral agents optimal management of a fish stock is characterized by a constant escapement policy, i.e. a constant size of the fish stock that remains in the sea after fishing. The subsequent literature has refined this work by adding multiple uncertainties (Clark and Kirkwood 1986, Sethi et al. 2005), costly capital adjustments (Singh et al. 2006), the choice of the regulatory instrument (Weitzman 2002), the spatial structure of the resource (Costello and Polasky 2008) and management with environmental prediction (Costello et al. 2001).

Only a few studies examine optimal feedback policies in a framework with risk aversion. Pindyck (1984) studies the management of renewable resources under uncertainty in continuous time, assuming a downward sloping demand function, which can be interpreted as reflecting risk-aversion of consumers. He offers analyt-

ical solutions for linear HCR and steady-state probability distributions for three special cases. Kapaun and Quaas (2013) examine how environmental uncertainty affects the optimal stock size and find that the optimal stock size could be higher or lower compared to the deterministic setting, depending, among other parameters, on the fishermen's degree of risk aversion. Using a similar model, Antoniadou et al. (2013) study the effects of risk aversion in a setting where several resource managers exploit a common-property resource and identify cases where risk reduces or increases the commons problem. The effect of risk aversion on the (maximum) expected sustainable yield (MESY) in a continuous-time model is studied by Ewald and Wang (2010). They model risk aversion in three different ways: 1) by including the variance as a penalty function, 2) by maximizing ESY under variance constraint or 3) by minimizing variance of the equilibrium distribution under an expectation constraint. In all cases they found that fisheries are in general willing to accept a lower expected sustainable yield in turn for a lower level of risk.

In this paper we extend this literature by characterizing how the optimal feedback policy (or: harvest-control rule) depends on the degrees of risk aversion of the relevant stakeholder groups, i.e. consumers and fishermen. We determine and compare the optimal harvest-control rules depending on the respective degrees of risk aversion. As we consider a stochastic stock growth model, harvest and/or stock biomass will change over time, i.e. over the realization of the random variable. To investigate these effects, we analyze the steady state probability distributions, in particular mean and standard deviation of escapement, stock, and harvest under different HCR. Under the optimal HCR for *risk neutral* stakeholders, stock biomass at the end of the fishing period, the escapement, will not change, such that all fluctuations will be absorbed by the annual harvest quantity. Under risk aversion both the escapement level and the harvest will fluctuate, and the higher the degree of risk aversion, the more the optimal HCR will shift uncertainty from harvest to the stock. Mean and standard deviation of harvest are monotonically decreasing with the degree of risk aversion, while the coefficient of variation of the resource stock will monotonically increase. The effect of risk aversion on mean

values of the resource stock is ambiguous. For lower degrees of risk aversion mean stock will decrease and will be lower than in the case with risk-neutral stakeholders; for sufficiently high degrees of risk aversion mean stock size will increase and will be higher than under risk neutrality.

The paper is structured as follows: In the following section we set up the stochastic fishery model with risk-averse stakeholders and apply it to the Baltic cod fishery in section 3. In section 4 we determine the optimal HCR analytically for a few special cases and numerically in the example of the Baltic cod and compare them with respect to their allocation of risk. We discuss our results in section 5.

2 Stochastic fishery model with risk-averse stakeholders

We consider a simple biomass model with stochastic stock growth in discrete time, where we allow the demand function to be downward sloping, and allow for risk aversion of fishermen against income fluctuations between years.¹ The growth of biomass x_t from time step t to $t + 1$ is described by the equation

$$x_{t+1} = z_t f(s_t), \quad (1)$$

where s_t denotes the escapement, i.e. the biomass that remains in the ecosystem after harvest h_t , such that $s_t = x_t - h_t$. The period between t and $t + 1$ is divided into two parts. In the first part harvesting takes place. In the second part the remaining fish biomass, i.e. the escapement, reproduces itself. The reproduction process is supposed to be sensitive to changing environmental conditions which are represented by the i.i.d. random variable z_t with $z > 0$ and mean equal to one. We assume that the fishery manager could observe the stock at the beginning of the period (x_t) with certainty. But when deciding about the optimal harvest in period t and thus about the optimal escapement level s_t , the fishery manager does

¹McGough et al. (2009) study a similar model, and derive optimal HCRs by linearizing the Euler equation in the neighborhood of the deterministic steady state.

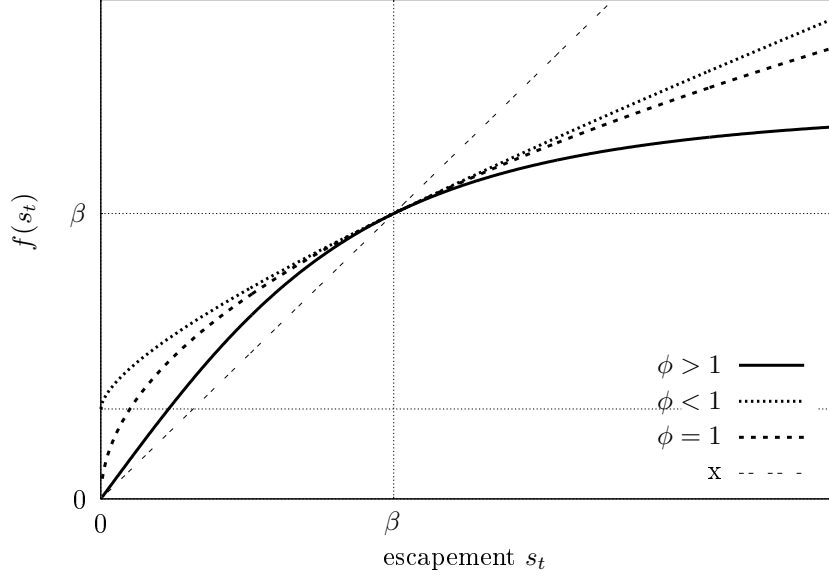


Figure 1: Illustrative examples for the expected biomass growth function (2).

not know how the fish stock will grow and is thus uncertain about stock biomass at the beginning of the following period x_{t+1} .

Expected biomass growth is described by the growth function $f(s_t)$, which is assumed to be increasing and concave, $f' > 0$ and $f'' < 0$. We will use the following specification (Antoniadou et al. 2013, Kapaun and Quaas 2013):

$$f(s) = (\alpha s^{1-\phi} + (1-\alpha)\beta^{1-\phi})^{\frac{1}{1-\phi}}, \quad (2)$$

with

$$f'(s) = \alpha (\alpha + (1-\alpha)s^{\phi-1}\beta^{1-\phi})^{\frac{\phi}{1-\phi}} > 0$$

$$f''(s) = -\alpha(1-\alpha)\phi s^{\phi-2}\beta^{1-\phi} (\alpha + (1-\alpha)s^{\phi-1}\beta^{1-\phi})^{\frac{\phi}{1-\phi}-1} < 0$$

The class of biomass growth functions contains, for different specifications of ϕ , a number of widely used specifications. For $\phi > 1$, it follows that $f(0) = 0$ and $f'(0) = \alpha^{\frac{1}{1-\phi}}$ is bounded for $s \rightarrow 0$, and $f(s) \xrightarrow{s \rightarrow \infty} (1-\alpha)^{\frac{1}{1-\phi}}\beta$ is also bounded. For $\phi < 1$, by contrast, $f(0) = (1-\alpha)^{\frac{1}{1-\phi}}\beta > 0$, $f'(s) \xrightarrow{s \rightarrow 0} \infty$, and $f'(s) \xrightarrow{s \rightarrow \infty} \infty$.

Two special cases of (2) are particularly well-known: For $\phi = 2$, we obtain the Beverton-Holt (1957) function $f_i(s) = s/(\alpha + (1-\alpha)/\beta s)$. For $\phi = 1$, (2) becomes

the iso-elastic function $f_i(s) = \beta^{1-\alpha} s^\alpha$, also known as the Cushing (1971) stock-recruitment function in fisheries, and used in resource economics, among others, by Levhari and Mirman (1980).

Harvesting takes place according to a generalized Schaefer production function for the instantaneous harvest rate \dot{h} within the fishing season, $\dot{h} = q(\tilde{x}) E_t \tilde{x}$, where $q(\tilde{x})$ is the catchability of the fish stock. We use E_t to denote the effort of harvesting fish and \tilde{x} to denote the stock, such that $\tilde{x} = x_t$ at the beginning of year t 's fishing season and $\tilde{x} = s_t$ at the end (Reed 1979, Clark 1990). Harvesting costs C are proportional to effort, $C = \zeta E_t$, with constant marginal costs ζ . The unit cost function of harvesting fish thus is $c(\tilde{x}) = \zeta/(q(\tilde{x}) \tilde{x})$. We use the common specification of the harvesting cost function $c(\tilde{x}) = \eta \tilde{x}^{-\chi}$ with $\chi \in (0, 1]$, which implies that unit harvesting cost are decreasing and convex in the stock size, i.e. $c' < 0$ and $c'' > 0$.

During the harvesting season each fish caught reduces the stock by one unit. Using p_t to denote the market price of fish in year t , annual profit π_t is obtained by integrating the flow of profits over the whole fishing season

$$\pi_t = \int_{s_t}^{x_t} (p_t - c(\tilde{x})) d\tilde{x} = p_t h_t - \frac{\eta}{1-\chi} (x_t^{1-\chi} - s_t^{1-\chi}). \quad (3)$$

The limit for $\chi \rightarrow 1$ exists and is given by $\pi_t = p_t h_t - \eta \ln(x_t/s_t)$.

The representative fisherman is risk-averse, captured by an instantaneous utility function with constant relative risk aversion θ ,

$$v(\pi_t) = \frac{\pi_t^{1-\theta} - 1}{1-\theta}. \quad (4)$$

For $\theta \rightarrow 1$, the representative fisherman's utility function is $v(\pi_t) = \ln(\pi_t)$.

For the representative consumer we assume a quasi-linear utility function $U(y, h) = y - u(h)$, where y is consumption of a numeraire (income), and $u(h)$ is utility of fish consumption. We will use the specification

$$u(h) = \frac{a h^{1-\epsilon}}{1-\epsilon}, \quad (5)$$

with $a > 0$ and $\epsilon > 0$. This utility gives rise to the iso-elastic inverse demand

function

$$p(h_t) = a h_t^{-\epsilon}. \quad (6)$$

We assume that $\epsilon < 1$, which means that revenues $p(h_t) h_t$ are strictly increasing with fish supply (which we regard to be a meaningful restriction), and furthermore guarantees $u(h_t) > 0$.

There are two equivalent ways of formulating the fishery manager's optimization problem. One is to maximize the present value of utility for the risk-averse fishermen, taking the market price of fish as given, and then using the inverse demand function (6) in the first-order condition that determines optimal harvest at a given stock size. The alternative, equivalent approach is to solve the following maximization problem:

$$\max \left\{ E \left[\sum_{t=1}^{\infty} \rho^{t-1} v \left(u(h) - \int_{s_t}^{x_t} c(\tilde{x}) d\tilde{x} \right) \right] \right\} \quad \text{subject to (1)} \quad (7)$$

where the operator E denotes the expectation over probability distribution of the random process $\{z_t\}$ and ρ is the discount factor $\rho = 1/(1+r)$, where $r > 0$ is the market interest rate.

Using $J(x)$ to denote the value function for optimization problem (7), the Bellman-equation reads

$$J(x) = \max_s \left\{ v \left(u(x-s) - \int_s^x c(\tilde{x}) d\tilde{x} \right) + \rho E [J(z f(s))] \right\}. \quad (8)$$

3 The Eastern Baltic cod fishery

The Baltic cod is one of the main commercial species in the Baltic Sea. Since the water in the Baltic Sea is brackish, it is a marginal area for cod. The fish population depends on fluctuating fresh water inflows from the North Sea to increase the salinity level to a degree where their eggs can hatch (Röckmann et al. 2007). Accordingly, the development of the Baltic cod is highly uncertain and represents a useful example for the stochastic stock growth model. The Baltic cod stock experienced a sharp decrease in the total stock biomass by the early 1990s, resulting

from deterioration in the environmental conditions and increasing fishing pressure (ICES 2012). In 2007 the EU multiannual management plan was set up which resulted in a slight recovery of the fish stock in the last years.

3.1 Historical and current HCR for Eastern Baltic cod

The current harvest-control rule for the Eastern Baltic cod fishery fixes a constant fishing mortality, i.e. the total allowable catch (TAC) is determined as a constant fraction of the stock size. This harvest-control rule is part of the multiannual plan for the cod in the Baltic Sea (European Commission 2007), set up by the European Union in 2007. The plan should ensure that Baltic cod stocks can be exploited under sustainable economic, environmental and social conditions. It further states that "[...] the Eastern stock must be rebuilt to safe biological limits and [...] levels must be ensured at which their full reproductive capacity is maintained and the highest long-term yields can be reached" (European Commission 2007, preamble, item 6). With other words, the multiannual plan should ensure a maximum sustainable yield (MSY). To realize this goal the fishing mortality rates should be gradually reduced and maintained at levels no lower than 0.3 on ages 4 to 7 for the Eastern Baltic cod stock in ICES area 25-32. Gradual reduction means a 10 % reduction of the previous year's fishing mortality rate. According to scientific advice the TAC is adopted that is the higher of the one applying the 10% reduction rule and the one resulting from the fishing mortality rate of 0.3. Should both result in a TAC that deviates by more than 15% in absolute value from the TAC of the preceding year, the TAC is adopted which is 15% higher or lower than the previous year's TAC. Thus, the multiannual management plan is not only aiming at the MSY but also at smoothed harvests over time. Negotiated with all stakeholders including fishermen's associations and fishing industries, the EU management plan is indeed addressed to risk averse stakeholders.

It is worth to have a look on the past fishing mortalities. Figure 2 shows the observed harvest and stock sizes for the period before the introduction of the

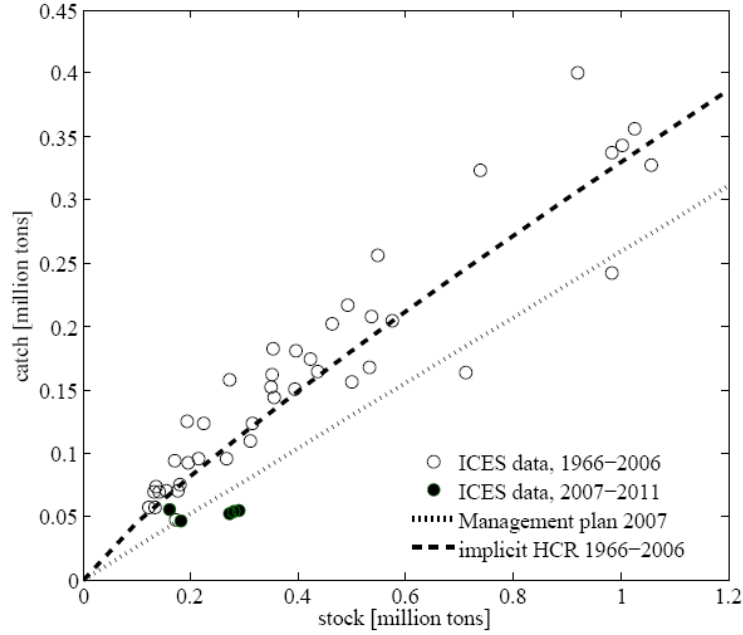


Figure 2: EU fishery policy and past fishery development for Eastern Baltic cod in ICES area 25-32. Open circles indicate data points before the implementation of the management plan (1966-2006), filled circles indicate data from 2007 onwards (ICES 2012).

management plan (1966 to 2007; white dots) and since the management plan is in place (2008 to 2012; black dots). To derive the implicit HCR for the years 1966-2007, i.e. before the multiannual plan was set up, we assumed an iso-elastic harvest curve $H = \alpha x^\beta$ and estimated the $\ln(H) = \ln(\alpha) + \beta \ln(x)$ by means of ordinary least squares. We get $\alpha = 0.33$ with the confidence interval [0.28 0.39] and $\beta = 0.87$ with the confidence interval [0.73 0.99], the resulting curve is shown as the dashed line in Figure 2. Thus the implicit HCR before the management plan was a concave function in the fish stock. Contrary, the new HCR with a constant fishing mortality rate of 0.3 is linear in fish stock (shown as the dotted line in Figure 2). It is obvious that harvest has been higher in the years 1966 to 2007 than under the current management strategy.

3.2 Estimation of model parameter values

For the estimation of the parameters of the biological growth function we use ICES (2012) assessment data for the Eastern Baltic cod in the ICES area 25-32 (years 1966 to 2012) for total biomass x_t , and harvest h_t , which is the sum of landings and discards, to calculate escapement $s_t = x_t - h_t$. We assume a stochastic Beverton-Holt (1957) growth function $f(s_t) = z_t \frac{s}{\alpha + \frac{1-\alpha}{\beta} s}$, i.e. we specify $\phi = 2$. For the numerical application, we further assume that the random variable z_t capturing environmental uncertainty is log-normally distributed. We take as exogenously given the estimate for the carrying capacity from Froese and Quaas (2011), which is $K = 2$ million tons. We therefore set $\beta = K$ and only estimate α . We econometrically estimate the parameter value α for the biomass growth function as well as the standard deviation of z_t by means of nonlinear least square regression for the model

$$X_{t+1} = \log \left(\frac{s}{\alpha + \frac{1-\alpha}{K} s} \right) + u_t, \quad (9)$$

assuming that $u_t = \log(z_t)$ is an independently and identically normally distributed error term. We obtain $\alpha = 0.53$ with 95% confidence interval (0.50; 0.56) and $\sigma_u = 0.14$.

For estimating the cost function (cf. equation 3) we use data on effort as days at sea for the Danish fleet² from Fiskeridirektoratet (2008) and Fiskeriregnskabsstatistik (2007) as well as ICES (2012) data for total biomass and the escapement calculated for the stock growth function. Using again the Levenberg-Marquardt algorithm for nonlinear least square we obtain $q_0 = 5.16$ and $\chi = 0.95$. For prices and unit effort costs ζ we use the estimates from Quaas et al. (2012). We get a unit harvesting cost parameter $\eta = 0.13$ billion Euros per million days at sea.

With regard to the elasticity of marginal utility, we make two alternative assumptions, $\epsilon_0 = 0$ for risk-neutral consumers and for risk-averse consumers $\epsilon_1 = 0.23$, which is the elasticity of the inverse demand for Baltic cod estimated by

²We assume that the Danish cost structure is representative for the whole Eastern Baltic cod fishery.

Nielsen (2006). To determine a_0 for risk neutral consumers and a_1 for risk averse consumers we again take Danish prices used for the estimation of the cost function. We then get the average price parameters $a_0 = 1.37$ and $a_1 = 2.54$, measured in billion Euros per million tons.³

To summarize we have the following optimization problem:

$$\begin{aligned} \max_{s_t} \pi_t &= E \left[\sum_{t=1}^T \rho^{t-1} \frac{1}{1-\theta} \left(\frac{a_i}{1-\epsilon_i} h^{1-\epsilon_i} - \int_{x_t}^{s_t} \frac{0.13}{\tilde{x}^{0.95}} d\tilde{x} \right)^{1-\theta} \right] \\ \text{s.t. } x_{t+1} &= z_t \frac{s}{0.53 + \frac{1-0.53}{2} s} \end{aligned} \quad (10)$$

where $i = 0, 1$ with $a_0 = 1.37$ if $\epsilon_0 = 0$ and $a_1 = 2.54$ if $\epsilon_1 = 0.23$, and $\rho = 1/(1+r)$ is the discount factor for a discount rate r .

For the preference parameters, the discount rate r and the coefficient of relative risk aversion θ , we use experimental observations from Andersen et al. (2008) who jointly elicit risk and time preferences in controlled experiments with subjects in Denmark⁴. The resulting values we use are $r = 0.1$ and $\theta = 0.74$ (Andersen et al. 2008, Table III). Although the estimated risk preference is not directly related to fishermen, it could be used as an upper bound for the fishermen's degree of risk aversion. Fishermen are likely less risk averse than the average Danish population, since a high risk sector as the fishery will only attract those individuals who are willing to accept the risk. In addition we also consider the case of risk neutral fishermen, i.e. we set $\theta = 0$.

4 Optimal harvest-control rules

In this section we derive the optimal harvest-control rules for three different scenarios: 1) consumers and fishermen are risk neutral, 2) only the fishermen are risk averse and 3) consumers and fishermen are both risk averse.

³We use the exchange rate of 7.45 between Danish crowns and euros.

⁴Again, we assume that findings for Denmark are representative for the whole Eastern Baltic cod fishery.

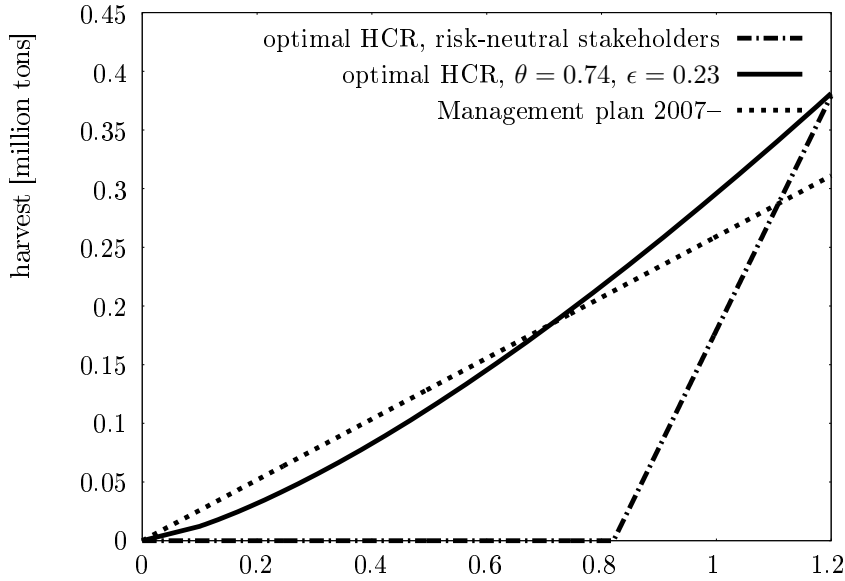


Figure 3: Optimal harvest-control rules for risk-neutral and for risk-averse stakeholders; and management plan for Eastern Baltic cod.

4.1 Analytical results

First we derive analytical results in a few special cases, stated in results 1 to 3:

Result 1. *If all stakeholders are risk neutral ($\theta = \epsilon = 0$), the optimal harvest-control rule is (weakly) convex.*

Proof: The optimal HCR under risk neutrality is a constant escapement policy, pictured as the dash-dotted line in Figure 3. Precisely, the corresponding HCR is $\hat{h}(x) = \min(0, x - s^*)$ (see Reed 1979). \square

As long as the stock at the beginning of the period is lower than the optimal escapement level s^* the optimal feedback solution $\hat{s}(x)$ equals the stock level and there is no harvesting at all, $\hat{h}(x) = 0$. When the stock level at the beginning of the period is higher than the optimal escapement level s^* the excess is harvested immediately, i.e. until the end of the fishing season, $\hat{h}(x) = x - s^*$. Above the threshold $x = s^*$ harvest therefore increases with the stock level to keep the escapement level constant. A consequence of the constant escapement policy is

that annual harvest could fluctuate heavily depending on the realization of the random variable. Under adverse environmental conditions harvest might be zero, under favorable environmental conditions harvest might be very high.

Result 2. *For risk-neutral consumers ($\epsilon = 0$), and stock-independent harvesting costs ($\chi = 0$), the optimal harvest-control rule is linear if $\theta = \phi$.*

Proof: Kapaun and Quaas (2013) show that under the given assumptions the value function is $J(x) = \psi_1 x^{1-\phi}/(1-\phi) + \psi_2$ with some constants $\psi_1 > 0$ and ψ_2 and that the optimal harvest-control rule is $\hat{s}(x) = \kappa x \iff \hat{h}(x) = (1-\kappa)x$, where $\kappa = (\rho \alpha E[z^{1-\phi}])^{\frac{1}{\phi}}$. \square

A similar closed-form solution can be also obtained in another special case of the model, where fishermen are assumed to be risk neutral, i.e. $\theta = 0$, and under the additional assumption that $\phi = \epsilon = \chi$. In Appendix A we show that for the optimal policy rule for this model is also $\hat{s}(x) = \kappa x$, where κ is given as the solution of the equation

$$(1-\kappa)^\phi \frac{1-\rho\alpha E[z^{1-\phi}]}{\kappa^\phi - \rho\alpha E[z^{1-\phi}]} = \frac{a}{\eta}. \quad (11)$$

Thus we have the following result.

Result 3. *For risk-neutral fishermen ($\theta = 0$), the optimal harvest-control rule is linear if $\epsilon = \chi = \phi$.*

The optimal policy in both special cases considered in Results 2 and 3 is characterized by a constant fishing mortality rate, i.e. a constant fraction of the fish stock will be harvested in every period. The optimal feedback curve is an increasing function of the stock level. In contrast to the constant escapement policy, which is optimal for risk-neutral stakeholders, harvest with risk-averse stakeholders is positive even for low stock levels. For high stock levels the harvest under a constant fishing mortality rate is lower than under a constant escapement policy. Given the intertemporal fluctuations of the stock growth and thus fluctuating stock levels at the beginning of the fishing period a constant fishing mortality rate results in smoothed harvest quantities over time.

The assumptions necessary for the analytical solutions are quite restrictive, and not in line with the empirical specification of the model parameters (see Section 3.2). In the following section we study optimal harvest-control rules numerically by allowing for different parameter constellations.

4.2 Numerical results for Eastern Baltic cod

Under risk aversion among fishermen and consumers the problem is non-linear in harvest and can only be solved numerically. To get a closed-loop solution for the optimal escapement level depending on the observed biomass level $\hat{s}(x)$, which can be easily transformed into an optimal harvest-control rule $\hat{h}(x) = x - \hat{s}(x)$, we thus approximate the Bellman-equation (8) applying the collocation method (Miranda and Fackler 2002), where the value function $J(x)$ is approximated by a finite linear combination of Chebychev polynomials. We use 77 collocation nodes on the interval $x \in [0.1, 3.9]$ million tonnes.⁵

Based on our analytical solutions in section 4.1 we can examine, how the optimal HCR will change with changing coefficients of risk aversion.

First we consider the conditions that lead to a linear optimal HCR (specified in Results 2 and 3) and ask how the shape of the optimal HCR changes if stakeholders are more or less risk averse than specified by the respective conditions. In Result 2 we assumed risk-neutral consumers, and showed that the optimal HCR is linear if the risk-aversion coefficient of fishermen (θ) coincides with the parameter ϕ of the biomass growth function. To numerically analyze how the shape of the optimal HCR changes when deviating from this assumption, we consider the specification $\theta = \phi = 2$ as the benchmark case. this means that we consider the Beverton-Holt specification for the biomass growth function (see Section 3.2). We then compare the resulting optimal HCR with the optimal HCR we obtain for values of θ that are slightly higher or lower than $\theta = 2$. We find that the optimal HCR is convex (concave) for values slightly below 2 (above 2). Figure 4 shows the difference in

⁵The optimization routines were implemented in Matlab. All programming codes will be made available as online supporting material.

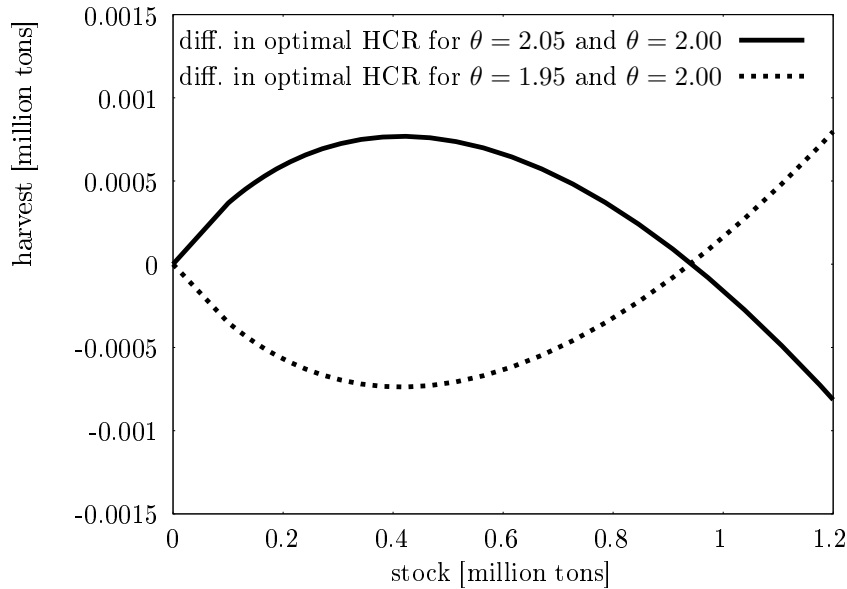


Figure 4: Convex and concave harvest-control rules.

optimal harvest between the benchmark case $\theta = 2$ and for values slightly above ($\theta = 2.05$) and below ($\theta = 1.95$). Under a convex (concave) HCR we observe lower (higher) harvest for lower stock levels and higher (lower) harvest for higher stock levels relative to the constant fishing mortality rate for $\theta = 2$. Thus, under a convex HCR harvest is less smoothed over time than under a concave HCR.

We now proceed by determining the optimal HCR for the Baltic cod fishery given that both stakeholders are risk averse, fishermen with a coefficient of risk aversion of $\theta = 0.74$ and consumers with $\epsilon = 0.23$ (cf. Section 3.2). The resulting optimal HCR is convex and shown as the solid curve in Figure 3. We see that for risk averse stakeholders, the optimal harvest as well as the optimal escapement monotonically increase with stock biomass. For low biomass levels we have higher harvest (lower escapement levels) under risk aversion than under risk neutrality. But for high biomass levels we observe optimal harvest levels (optimal escapement levels) which are below (above) those under risk neutrality. The feedback solution for risk averse stakeholders results in smoothed harvest. When the fish stock at the beginning of the period is low, as a result of adverse environmental conditions,

harvest is not zero but positive. When the stock at the beginning of the period is high, a result of favorable environmental conditions, the optimal feedback solution yields lower harvest than under the constant escapement policy. Therefore the extreme harvest levels are eliminated and harvest over time is smoothed.

4.3 Risk allocation under optimal harvest-control rules

In the previous section we have found that the optimal HCR under risk aversion is flatter than for the case of risk-neutral stakeholders and thus will lead to smoothed harvest over time, i.e. the risk of heavily fluctuating harvest is dampened. In this section we will focus on the question how the risk is allocated under different HCR.

To analyze the risk allocation under the different optimal HCR we numerically examine the steady-state probability distributions of stock, escapement and harvest. For that sake, we consider a million simulations over a time period of 25 periods (after which we assume that the steady state is reached), starting at the current (2012) stock level of 290.000 tons. Figure 5 shows the steady state distribution of stock, escapement and harvest for the year $t = 25$ for three different HCRs: 1) the optimal HCR for risk-neutral stakeholders, i.e. the constant escapement policy, 2) the optimal HCR for risk averse stakeholders with $\theta = 0.74$ and $\epsilon = 0.23$ and 3) the HCR with a constant fishing mortality $F = 0.3$ as specified in the multiannual management plan.

First we consider the constant escapement policy for risk neutral stakeholder. Here, the harvest quantities vary considerably around the mean harvest of 314,600 tons. The lowest observed harvest quantity is 0 tonnes, the highest 1,298,400 tonnes. The coefficient of variation (CV) for harvest is 0.50. The escapement level barely fluctuates with a CV of only 0.01, while the stock level exhibits a coefficient of variation of 0.14.

When both stakeholders are risk averse the harvest varies between 83.600 and 971.500 tons around the mean harvest of 304,800 tons with a coefficient of variation (CV) of 0.25, which is considerably lower compared to 0.50 under the constant

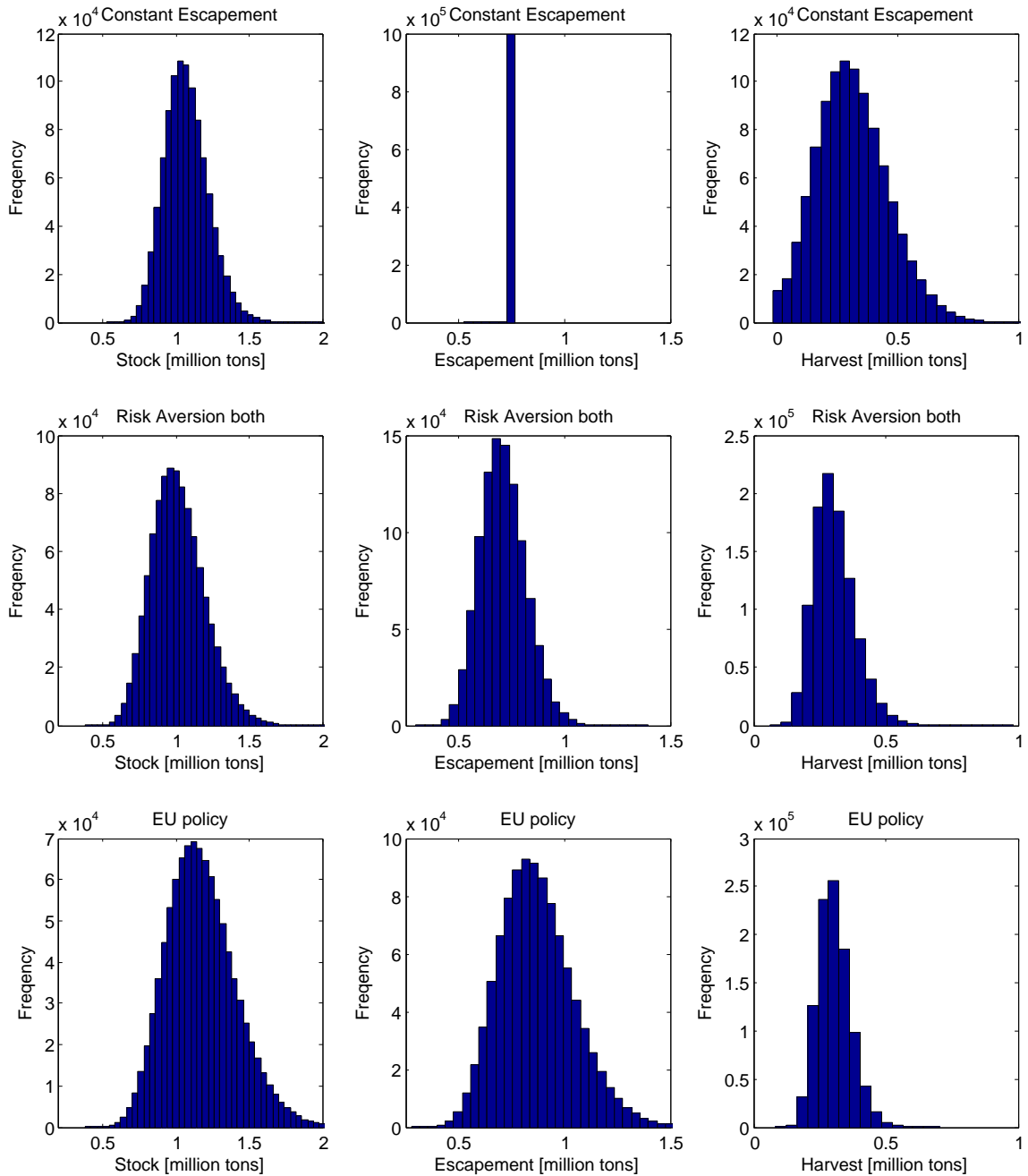


Figure 5: Histograms of the steady-state distributions of stock, escapement, and harvest under the optimal HCR for risk-neutral stakeholders (top row); risk-averse stakeholders (middle row); and the current management plan for Eastern Baltic cod (bottom row).

escapement policy. We also see that stock and escapement fluctuates more under risk aversion than under constant escapement policy. The CV for the escapement increases from 0.01 under the constant escapement policy to 0.15 under the optimal HCR for risk averse stakeholders. The increase in the variation for the stock is relatively lower with 0.14 for the constant escapement policy and 0.18 for the case of risk aversion. Thus, less fluctuations in harvest are primarily compensated by the escapement level at the end of the period and only second-tier by the stock level at the beginning of the period. Hence, smoothed harvest go along with strongly fluctuating escapement levels. In other words, the risk is mainly shifted from harvest to escapement.

For a deeper analysis of this effect we examine the effect of increasing degrees of risk aversion on the mean and standard deviation of stock x_t , escapement s_t and harvest h_t . We only vary risk aversion among fishermen, keeping the risk aversion of consumer constant at $\epsilon = 0.23$, since fishermen have less possibilities to substitute Baltic cod with other species and thus higher degrees of risk aversion are more plausible. The results are plotted in Figure 6. As can be seen, mean harvest monotonically decreases with increasing risk aversion among fishermen. Simultaneously the variation in harvest is also decreasing. On the contrary variation in stock and escapement will monotonically increase with increasing risk aversion. The higher the degree of risk aversion, the more the optimal HCR will shift uncertainty from harvest to the stock.

The effect of risk aversion on the stock and escapement is ambiguous. Under low risk aversion, as in our example for values $\theta < 1$, mean level for stock and escapement are lower compared to the case of risk neutrality among fishermen. It is also lower than the mean levels for the case of risk-neutral stakeholders, i.e. compared to the constant escapement policy. Relatively higher degrees of risk aversion, in our example values of θ well above one, then lead to increasing mean levels of stock and escapement, even compared to the constant escapement policy. In our example of the Baltic cod fishery with a moderate risk aversion among fishermen of $\theta = 0.74$ we observe a lower mean stock size than in the case

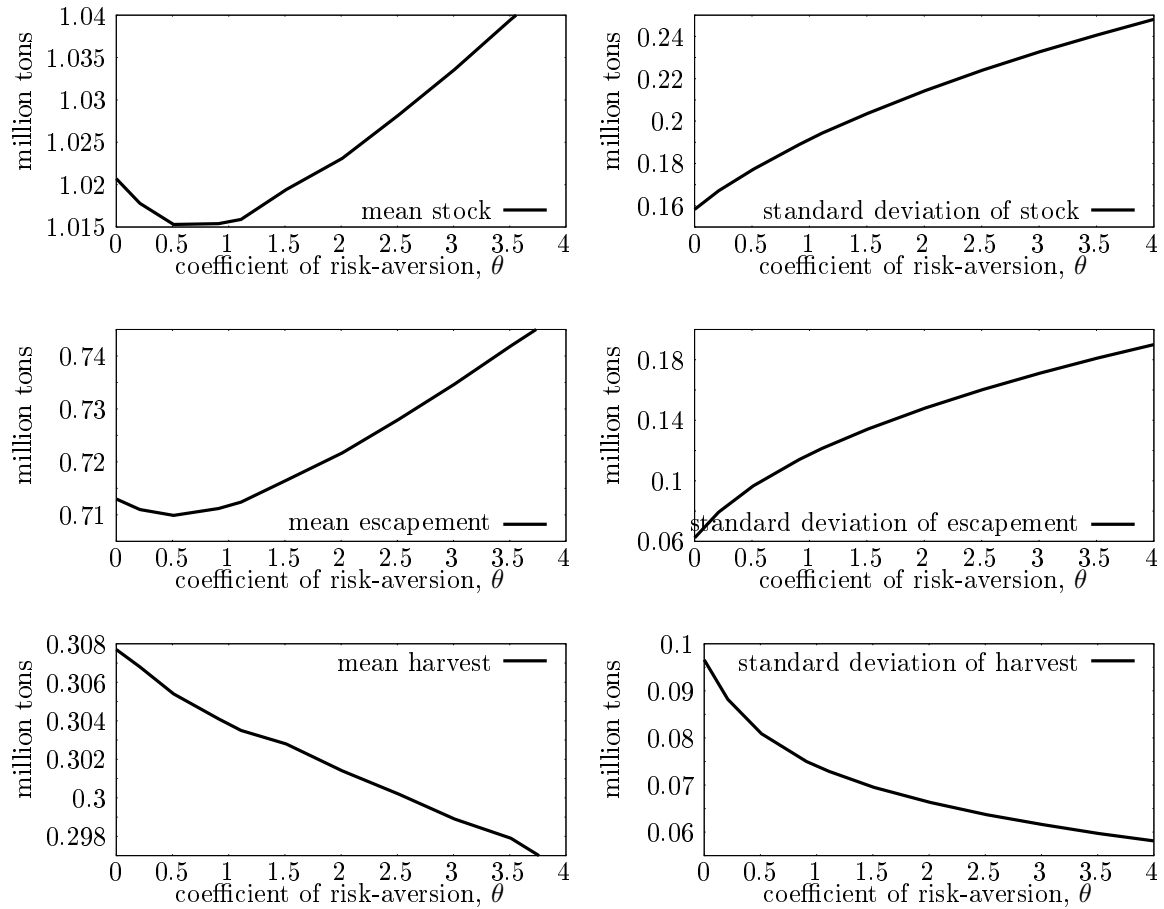


Figure 6: Mean and standard deviation of steady-state distributions for stock, escapement, and harvest under optimal harvest-control-rules for different coefficient of risk-aversion of fishermen risk-aversion.

of risk-neutral fishermen and/or consumers. Thus, risk averse stakeholders are willing to accept a lower mean harvest for less variations in harvest, even if it comes to the expense of a lower mean level of the resource stock. This is in line with the findings of Ewald and Wang (2010) who found lower expected sustainable yield values under risk aversion, although in a static continuous-time model with a stochastic differential equation of the Ito-type.

5 Discussion and Conclusion

In this paper we have analyzed how the optimal harvest-control rule for a fishery under environmental uncertainty depends on the risk-aversion of stakeholders. We have derived analytical results for a few special cases and quantitative results for the Eastern Baltic cod fishery.

We have shown that the optimal policy under risk aversion differs considerably from the common constant escapement policy under risk neutrality. In contrast to constant escapement levels under risk neutrality we get increasing escapement levels in the optimal feedback policy for risk averse agents resulting in monotonically increasing harvest. We found that the optimal harvest-control rule will be convex for relatively low degrees of risk aversion and will be concave for relatively high degrees of risk aversion. A linear HCR will be optimal under some restrictive assumptions with respect to the cost structure, the stock growth function and the coefficients of risk aversion of the stakeholders.

Considering intertemporal fluctuations we found that the constant escapement policy for risk neutral agents results in strong fluctuations of harvest whereas we observe smoothed harvest and strongly fluctuating escapement under an optimal policy for risk averse agents. The higher the degree of risk aversion, the more the optimal HCR will shift uncertainty from harvest to the stock. The intuitive reason is that the optimal HCR makes use of the natural insurance function of the ecosystem (Quaas and Baumgärtner 2008). At the same time risk aversion results in a lower mean harvest, whereas the effect on the mean resource stock is ambiguous. Under moderate degrees of risk aversion we observe a lower mean resource stock compared to the case of risk neutrality. Only relatively high degrees of risk aversion ensure a more conservative resource management.

In section 4.1 we have shown that a constant fishing mortality rate would be optimal in a special case when demand is perfectly elastic, harvesting costs are stock independent and the fishermen have a coefficient of risk aversion equal to the elasticity parameter ϕ of the biomass growth function. If the stock growth

follows a Beverton-Holt function, i.e. $\phi = 2$, and the degree of risk aversion would be $\theta = 2$, the optimal HCR $\hat{h}(x) = \left(1 - (\rho \alpha E[z^{1-\phi}])^{\frac{1}{\phi}}\right) x$ would yield $F = 0.36$, which is very similar to the constant fishing mortality rate of $F_{EU} = 0.3$ as set up by the EU fishery management plan.

However, experimental evidence shows that the degree of risk aversion is much smaller than 2, and more likely to be about $\theta = 0.74$. Using additionally an elasticity of the inverse demand function for cod of $\epsilon = 0.23$, we have found that the optimal HCR for Baltic cod is convex, and thus differs significantly from the current and historical HCR for that fishery. In particular for the prevailing, relatively small stock sizes, optimal harvest would be much lower, and stock rebuilding would be much faster, than under the current multiannual management plan for the Baltic cod.

Appendix

A Optimal HCR with risk-averse consumers

Guessing the value function $J(x) = \psi_1 x^{1-\phi}/(1-\phi) + \psi_2$ with some constants ψ_1 and ψ_2 , the first order condition of the optimization problem on the right-hand side of the Bellman equation (8) can be written as

$$\frac{a}{(x-s)^\phi} - \frac{\eta}{s^\phi} = \rho \psi_1 E[z^{1-\phi}] \frac{\alpha}{s^\phi} \quad (12)$$

Now guessing $\hat{s}(x) = \kappa x$ with some $\kappa > 0$ we obtain

$$\frac{a}{(1-\kappa)^\phi} - \frac{\eta}{\kappa^\phi} = \rho \psi_1 E[z^{1-\phi}] \frac{\alpha}{\kappa^\phi} \quad (13)$$

Using $J(x) = \psi_1 x^{1-\phi}/(1-\phi) + \psi_2$ and $\hat{s}(x) = \kappa x$ in the Bellman equation (8), we obtain

$$\begin{aligned} \psi_1 \frac{x^{1-\phi}}{1-\phi} + \psi_2 = & a \frac{(x(1-\kappa))^{1-\phi}}{1-\phi} - \frac{\eta}{1-\phi} x^{1-\phi} (1-\kappa^{1-\phi}) \\ & + \rho E \left[\frac{\psi_1}{1-\phi} z^{1-\phi} (\alpha (\kappa x)^{1-\phi} + (1-\alpha) \beta^{1-\phi}) + \psi_2 \right] \end{aligned} \quad (14)$$

By equating coefficients, we obtain

$$\psi_1 = a(1 - \kappa)^{1-\phi} - \eta(1 - \kappa^{1-\phi}) + \psi_1 \rho E[z^{1-\phi}] \alpha \kappa^{1-\phi} \quad (15)$$

$$= \frac{a}{(1 - \kappa)^\phi} - \eta - \kappa \left(\frac{a}{(1 - \kappa)^\phi} - \frac{\eta}{\kappa^\phi} - \rho \psi_1 E[z^{1-\phi}] \frac{\alpha}{\kappa^\phi} \right) \quad (16)$$

Using this in (13) leads to $(1 - \kappa)^\phi \frac{1 - \rho \alpha E[z^{1-\phi}]}{\kappa^\phi - \rho \alpha E[z^{1-\phi}]} = \frac{a}{\eta}$.

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How to deal with Ocean Acidification in Fisheries Management - An example on Norwegian Coastal Cod

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Abstract.

In this paper I examine effects of ocean acidification on the optimal fishery management, in particular for the example of the Norwegian coastal cod. I summarize recent biological studies on the effects of decreasing pH-values on different fish species in the North Atlantic and demonstrate how these findings could be scaled from the physiological level to population processes like the stock-recruitment relationship. Applying an age-structured fishery model to the Norwegian coastal cod fishery I find that stock biomass and harvest possibilities will decrease with increasing ocean acidification. While the detrimental consequences will be moderate under predicted pH-values for the year 2300, an extreme upwelling scenario will have severe effects on stock and harvest, in particular it destabilizes the system and fosters pulse fishing. My results are meant as a first step towards including experimental data on biological effects of ocean acidification into ecological-economic models. Further research will be needed, in particular on the ecosystem level, to get reliable results as a basis for adaptive fishery management.

Keywords: fisheries, fishery economics, ocean acidification, Norwegian coastal cod

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1 Introduction

Ocean acidification, caused by rising anthropogenic CO_2 emissions, is supposed to influence the marine ecosystem by decreasing the pH-value and changing the chemical composition of seawater. Global surface pH has already decreased by more than 0.1 units since preindustrial times and might decrease by up to 0.4 additional units by 2100 (Caldeira and Wicket, 2003; Caldeira and Wicket, 2005; Denman et al., 2011). In the last years oceanographers examined possible effects of ocean acidification on marine flora and fauna. Decreasing ocean pH, accompanied by decreasing carbonate ion concentration and calcium carbonate mineral saturation, will negatively effect growth of calcium carbonate shells and skeletons by many marine plants and animals (Cooley and Doney, 2009). Although ocean acidification will primarily effect calcifying organisms, some fish species could also be sensitive to decreasing ocean pH-values. In particular early life history stages in fish development, like eggs and larvae, are believed to be vulnerable against acidic conditions as they lack specialized internal pH regulatory mechanisms (Frommel et al., 2012a). Thus, by deteriorating recruitment conditions for the fish stock ocean acidification could induce declines in fishing possibilities. In this article I examine how optimal fishery management should change with rising ocean acidification.

Research on the effects of ocean acidification to fisheries management is a new field. To my knowledge there is no study yet, which determines the optimal fishery management under progressive ocean acidification. This may be due to the still very limited knowledge about the consequences of decreasing pH-values on the physiology of different fish species. Some recent studies imply detrimental effects of ocean acidification on the early-life stages of certain fish species, but detailed long-term studies are still missing.

More is known about the effects on calcifying organism, like mollusks and crustaceans. There are already a few articles dealing with the economic consequences for commercial fisheries, in particular the study of Cooley and Doney (2009) about the commercial US fisheries for mollusks. In US fisheries mollusks count for 19%

of the total ex-vessel value. Another 30% result from crustaceans and 24% from fish that prey directly on calcifiers. “To provide a starting point for ocean acidification’s impact on mollusks,... [they] assume a simple one-to-one correspondence between reduced calcification for a particular atmospheric CO_2 level and reduced commercial mollusk harvests” (Cooley and Doney, 2009). By doing so they predict a 6%-25% decrease in harvest accompany 0.1-0.2-unit pH decrease over 50 years, resulting in net present value loss of \$ 1.7-10 billion through mid-century. Narita et al. (2012) extend this analysis for mollusks to a partial equilibrium consideration. They in turn yield annual losses of \$ 6 billion under constant demand of mollusks up to \$ 100 billion for an increasing demand with future income rise. Frameworks and methods to study socio-economic impacts of ocean acidification in the Mediterranean Sea are discussed by Rodrigues et al. (2012), including effects on tourism, fishery and aquaculture.

In this paper I will examine which effects ocean acidification could have on the optimal fishery management. In a first step I will summarize the available studies dealing with the consequences of decreasing pH-value on the fish development, concentrating on fish species in the North Atlantic and Baltic Sea. Based on the experimental results for Norwegian coastal cod by Frommel et al. (2012a) I demonstrate, how results could be scaled from physiological responses to population processes. Precisely I translate the results from Frommel et al. (2012a) into the Ricker stock-recruitment relationship, demonstrating that recruitment success will decrease. Using the resulting stock-recruitment relationships in an age-structured fishery model I show, how optimal management would change under two scenarios of future ocean acidification. I found, that a CO_2 level of $1800\mu atm$, which is supposed to occur in the year 2300, will have a moderate effect on the optimal fishery management. Optimal stock size as well as optimal harvest will decrease, but will be still on a relatively high level. Under the extreme scenario of $4200\mu atm$ I observe severe effects on the fishery with average harvest rates of only 40% of those in the control scenario. In addition I found a tendency to pulse fishing in the high scenario, thus ocean acidification destabilizes the fishery.

The paper is structured as follows: In the following section I summarize biological studies about effects of decreasing pH for the development of fish stocks. In section 3 I demonstrate how experimental results can be scaled from physiological responses to the population process of recruitment. I set up the age-structured fishery model in section 4 and apply it to the Norwegian coastal cod fishery in section 5. I summarize and discuss my results in section 6.

2 Ocean acidification and its effect on fish development

The accumulation of carbon dioxide in the atmosphere will lower the pH in ocean waters, a process termed ocean acidification. About a third of excess CO_2 in the atmosphere will be dissolved in ocean waters, leading to an estimated drop in pH of 0.4 units (corresponding to a partial pressure of CO_2 in seawater in micro-atmosphere of $\sim 1000\mu atm$) globally by the year 2100 and up to 0.8 units ($pCO_2 \sim 2000\mu atm$) by the year 2300 (Caldeira and Wickett, 2003; Caldeira and Wickett, 2005; IPCC 2007, Frommel et al., 2012a)¹. Locally the effects can be even more severe, in particular in coastal regions pCO_2 -values above $4000\mu atm$ in the future could be reached in habitats where e.g. cod larvae occur (Thomsen J, et al., 2010).

Ocean acidification could influence many physiological processes of fish as e.g. otolith development, basal metabolic costs, aerobic scope, O_2 consumption, thermal tolerance, fertilization success, egg hatching and embryonic development. This in turn may lead to reduced growth and reproductive output, increased predation and mortality, alteration in feeding rates, and behavior, among other things (for more details see Le Quesne and Pinnegar, 2012). While it is widely accepted that

¹The measurement unit micro atmosphere (μatm) for the partial pressure of CO_2 in seawater accords to the probably more common concentration measure 'parts per million ppm ', i.e. $1\mu atm \sim 1ppm$ (See also Ishimatsu and Dissanayake, 2010). Since the data I use in the example of Norwegian coastal cod deals with μatm I will also refer to this measurement unit.

adult fish will most likely remain relatively unaffected by changes in seawater pH, early life-history stages are potentially more sensitive as they lack specialized internal pH regulatory mechanism (Ishimatsu and Dissanayake, 2010; Frommel et al., 2012a; Frommel et al., 2012b).

Several recent studies examine the effect of ocean acidification on early life-history stages of different fish species, e.g. Baltic cod, Atlantic cod and Atlantic herring. For the Baltic cod (*Gadus morhua callarias*) no detrimental effects of ocean acidification were found. Neither the fertilization nor the early life-history stages including hatching were influenced by higher CO_2 levels (Frommel et al., 2010, Frommel et al., 2012b). Biologists assume that the Baltic cod already adapted to higher concentration of CO_2 . In particular in the Bornholm Basin, the main spawning site of eastern Baltic cod, the CO_2 concentration is already relatively high, mainly due to high eutrophication supporting microbial activity and permanent stratification with little water exchange. The development of the Baltic cod seems therefore robust to even high levels of ocean acidification (Frommel et al., 2012b).

For the Atlantic cod (*Gadus morhua*), in particular for the Norwegian coastal cod the laboratory-based study from Frommel et al. (2012a) found detrimental effects of ocean acidification on larvae. Increasing CO_2 concentration will cause severe to lethal tissue damage in many internal organs of the larvae. In a scenario with $1800\mu atm$ 12 % of the larvae had severe damages like multiple organ defects, in a scenario with $4200\mu atm$ this was the case for 75% of the larvae, whereas no damages were found in the control scenario ($380\mu atm$). Frommel et al. (2012a) assume that most of these damages would enhance the mortality of larvae in the open ocean. As larvae survival is the bottleneck to recruitment, ocean acidification has the potential to act as an additional source of natural mortality, affecting populations of already exploited fish stocks (Frommel, 2012a, Voss et al., 2012).

Another study on Atlantic herring (*Clupea harengus* L.) indicates that ocean acidification could affect the metabolism of herring embryos negatively and could result in smaller and slower-growing individuals with a lower survival potential

due to lower feeding success and increased predation mortality (Franke, 2011). A negative linear correlation between ocean acidification and metabolism could no longer be detected when the highest treatment level (4635 μatm) was deleted. It is thus possible that negative effects only occur beyond a certain tipping point.

A similar study on the inland silverside (*Menidia beryllina*) affirms reduced survival and growth rates for higher CO_2 levels (Baumann et al., 2011). At a CO_2 level of ~ 1000 ppm (μatm) larvae survival was reduced by 74%, average length by 18% compared to the present-day CO_2 level of ~ 400 ppm (μatm). Reduced larval growth induces higher mortality rates, because slower-growing larval cohorts are vulnerable to predators for a longer time and therefore experience higher cumulative mortalities (Baumann et al., 2011).

Beside the direct influence on early-life stages some species could be indirectly affected by ocean acidification. Higher physiological stress due to more acidic water could cause a higher oxygen demand. Oxygen is in particular needed for fish growth. In regions where the oxygen concentration is already low ocean acidification could further slow down growth and could result in lower maximum length and weight (Teschner et al., 2010). Alternatively, a shift towards oxygen richer regions might occur, leading to a lower harvestable biomass (Cheung et al., 2011). Indirect effects of higher CO_2 -level on the food web, especially phytoplankton, are also possible. Changes in phytoplankton size structure affect the amount of energy transferred to higher trophic levels (fish) which in turns could have positive or negative consequences for fish growth and carrying capacity (Cheung et al., 2011).

To sum up, fish development could be negatively influenced by ocean acidification, especially in the process of recruitment. But further analyses are needed to examine the long-term effects of higher CO_2 -levels in ocean waters on fish stocks and their biotic environment.

3 Scaling from physiological responses to population processes

Recent biological studies mostly refer to effects of ocean acidification on physiological processes. Considering the potential impact of ocean acidification on fisheries requires scaling from physiological responses to population- and ecosystem-level processes. A simple way is to consider how ocean acidification could modify the parameters of growth, mortality and reproduction in a single-species model (Le Quesne and Pinnegar, 2012). Here I concentrate on the modification of the parameters of the stock-recruitment relationship in an age-structured fishery model.

I assume, that egg production, N_0 , is proportional to spawning stock, ssb , i.e. $N_0 = f ssb$, where f is the net fecundity in the population (Hilborn and Walters, 1992). The development of the early-life history follows $\frac{dN}{dt} = -Z_t N$, where $N(0) = N_0$, T is the life stage where the recruits enter the fish stock, i.e. $N(T) \equiv R$ and Z_t denotes the mortality at life stage t . The mortality at life stage t , Z_t , is made up of both density-independent and density-dependent effects: $Z_t = a + b ssb$, where a refers to the density-independent mortality and b accounts for density-dependency, i.e. the spawning stock inhibits the population of young fish before recruitment, e.g. through cannibalism (Quinn and Deriso, 1999). The differential equation then becomes:

$$\frac{dN}{dt} = -(a + b ssb)N \quad (1)$$

with its solution

$$N(t) = N_0 e^{-(a+b ssb)t}. \quad (2)$$

For $t = T$, $N_0 = f ssb$ and $N(T) \equiv R$ equation (2) becomes the Ricker stock-recruitment function

$$R = f e^{-aT} ssb e^{-bT ssb}, \quad (3)$$

or, in its usual notation $R = \alpha ssb e^{-\beta ssb}$, where $\alpha = f e^{-aT}$ and $\beta = bT$.

Following Frommel et al. (2012a) ocean acidification causes severe tissue damages in the larvae which is likely to result in a higher larval mortality rate. For

simplicity I assume that these effects will only influence the density-independent mortality during the whole recruitment phase aT and that the severe tissue damages in the larvae will result in an increased mortality of exact the same magnitude. Thus, I assume that aT will change such that $(aT)' = (1+d)aT$, where d is the rate of acidic-induced enhanced larvae mortality during the whole recruitment phase. For the parameter α I then get $\alpha' = f e^{-(1+d)aT}$. After rearranging I have the following relationship between the original parameter α and the altered parameter α' :

$$\alpha' = f^{-d} \alpha^{1+d}$$

As found by Franke et al. (2011) and Baumann et al. (2011) ocean acidification could enhance the vulnerability of larvae to predation. It is also possible that ocean acidification affects the food chain, positively by increasing the food supply or negatively by limiting food supply. Both incidents would affect the density-dependent part of the mortality rate Z_t , i.e. the parameter bT . A higher (lower) density-dependent mortality would imply higher (lower) values of bT and thus would translate into an one-to-one increase (decrease) in the parameter β .

To sum up, ocean acidification is likely to cause a decrease in the parameter α of the Ricker stock-recruitment function and/or an increase (decrease) in the parameter β . A decrease in α together with an increase in β would unambiguously result in a lower stock-recruitment curve and thus in lower recruitment success. If both, α and β , decrease, the overall effect on the recruitment would be ambiguous:

$$R_1(ssb) : \begin{cases} < R_0(ssb) & , \text{ if } ssb < -\frac{\log(\alpha_0) - \log(\alpha_1)}{\beta_1 - \beta_0} \\ > R_0(ssb) & , \text{ else} \end{cases}$$

For low (high) stock levels the recruitment under ocean acidification, i.e. $R_1(ssb)$ with $\alpha_1 < \alpha_0$ and $\beta_0 < \beta_1$, will be lower (higher) than the recruitment under current pCO_2 -levels $R_0(ssb)$.

4 Age-structured fishery model

For my age-structured fishery model I refer to the model by Tahvonen et al. (2012) who determined optimal harvesting of an age-structured fishery. Let x_{at} denote the number of fish (in 10^3 individuals) in each age class $a = 1, \dots, A$ and at the beginning of each period $t = 0, 1, \dots$. The population dynamics of the age-structured fish stock are given by:

$$x_{1,t+1} = r \left(\sum_{a=1}^A m_a w_a x_{at} \right) \equiv R(ssb_t), \quad (4)$$

$$x_{a+1,t+1} = b_a (x_{at} - \phi_a E_t x_{at}), \quad a = 1, \dots, A-2, \quad (5)$$

$$x_{A,t+1} = b_{A-1} (x_{A-1,t} - \phi_{A-1} E_t x_{A-1,t}) + \quad (6)$$

$$b_A (x_{At} - \phi_A E_t x_{At}), \quad (7)$$

where $b_a, a = 1, \dots, A$ are age-specific survival rates, $m_a, a = 1, \dots, A$ the proportion mature at age a , w_a the weight of a fish at age a (in kg), $\phi_a, a = 1, \dots, A$ are age-specific catchability parameters, and $R(ssb_t)$ is the Ricker stock-recruitment function (see section 3) with the spawning stock biomass ssb_t given by $\sum_{a=1}^A m_a w_a x_{at}$. The total annual catch (in tons) is given by $H_t = \sum_{a=1}^A w_a \phi_a E_t x_{at}$. Solving for fishing effort in year t , E_t , I get:

$$E_t = \frac{H_t}{\sum_{a=1}^A w_a \phi_a x_{at}}, \quad (8)$$

such that (5) and (7) can be rewritten as

$$x_{a+1,t+1} = b_a x_{at} - H_t G_{at}, \quad a = 1, \dots, A-2, \quad (9)$$

$$x_{A,t+1} = b_{A-1} x_{A-1,t} + b_A x_{At} - H_t G_{A-1,t}, \quad (10)$$

where

$$G_{at} = \frac{b_a \phi_a x_{at}}{\sum_{a=1}^A w_a \phi_a x_{at}} \quad (11)$$

$$G_{A-1,t} = \frac{b_{A-1} \phi_{A-1,t} x_{A-1} + b_A \phi_{A,t} x_A}{\sum_{a=1}^A w_a \phi_a x_{at}}. \quad (12)$$

Thus, $G_{at}, a = 1, \dots, A - 1, t = 0, 1, \dots$ are variables that transform the total catch H_t to the numbers of fish harvested from each age class.

The objective function I apply is to maximize the net present value of utility from harvesting fish:

$$\sum_{t=0}^{\infty} \rho^t \frac{1}{1-\nu} [p H_t - C(H_t, X_t)]^{1-\nu}, \quad (13)$$

where $X_t = \sum_{a=1}^A w_a x_{at}$ denote the total stock biomass in period t.

The Lagrangian and the first order conditions are

$$L = \sum_{t=0}^{\infty} \rho^t \left(\begin{array}{l} \frac{1}{1-\nu} [p H_t - C(H_t, \sum_{a=1}^A w_a x_{at})]^{1-\nu} + \\ \lambda_{1t} \left(r (\sum_{a=1}^A m_a w_a x_{at}) x_{1,t+1} \right) + \\ \sum_{a=1}^{A-2} \lambda_{a+1,t} (b_a x_{at} - H_t G_{at} - x_{a+1,t+1}) + \\ \lambda_{At} (b_{A-1} x_{A-1,t} + b_A x_{At} - H_t G_{A-1,t} - x_{A,t+1}) \end{array} \right), \quad (14)$$

$$\frac{\partial L}{\partial H_t} \rho^{-t} = (p H_t - C(H_t, X_t))^{-\nu} \left(p - \frac{\partial C(H_t, X_t)}{\partial H_t} \right) - \sum_{a=1}^{A-1} \lambda_{a+1,t} G_{at} = 0, \quad (15)$$

$$\begin{aligned} \frac{\partial L}{\partial x_{a+1,t+1}} \rho^{-t} &= \rho (p H_{t+1} - C(H_{t+1}, X_{t+1}))^{-\nu} \left(-\frac{\partial C}{\partial x_{a+1,t+1}} \right) + \\ &\quad \rho \lambda_{1,t+1} r' m_{a+1} w_{a+1} - \lambda_{a+1,t} + \\ &\quad \rho \lambda_{a+2,t+1} b_{a+1} - \rho H_{t+1} \sum_{j=1}^{A-1} \lambda_{j+1,t+1} \frac{\partial G_{j,t+1}}{\partial x_{a+1,t+1}} = 0 \end{aligned} \quad (16)$$

5 Application to Norwegian coastal cod

I apply my age-structure fishery model to the Norwegian coastal cod (NCC) fishery. The Norwegian coastal cod live and spawn in a large number of fjords along the Norwegian coast north of 62° latitude (ICES 2012, Frommel et al. 2012a). As Frommel et al. (2012a) point out these high latitudes are particularly impacted by future ocean acidification with predicted pH values of 7.7 to occur by 2100, and even lower values in some parts of the Arctic Ocean, since cold water is able to take up relatively more atmospheric CO_2 . In general a higher acidity

of coastal waters could be caused by persistent or episodic acid inputs resulting from river water, upwelling of deep CO_2 -rich, low pH seawater, bottom sediments, atmospheric deposition of terrigenous materials, or acidic wastage of aquaculture (Ishimatsu and Dissanayake, 2010). Frommel et al. (2012a) investigate the effects on ocean acidification on NCC larvae in three different scenarios: a control scenario with $380\mu atm$, representing the current pCO_2 -level, a medium scenario with $1800\mu atm$, a level which is likely to occur by the year 2300, and a high scenario with $4200\mu atm$ as an extreme coastal upwelling scenario possible for the spawning areas of NCC.

The NCC is fished throughout the year within the 12 nautical mile zone at the Norwegian coast. Biomass and catches had been quite high in 1980s and in the middle of the 1990s with an average of 350,000 tonnes or 80,000 tonnes, respectively, but have been at relatively low levels (180,000 tonnes; 35,000-40,000 tonnes) in the last 10 years (Figure 1, ICES 2012). Recreational fisheries take an important fraction of the catches, especially near coastal cities and in some fjords where commercial fishing activity is low. Estimated catches in the recreational fishery represents about 35% of the total catch in recent years (ICES, 2011)

The habitat of the NCC overlaps with the habitat of the Northeast Arctic cod (NEAC). Total allowable catches (TAC) is a combined TAC for both the NEAC stock and NCC stock. Both species can only be distinguished by examining their otoliths. Samplings from cod catches taken inside 12 n.mile in 2010 and 2011 yield a portion of NCC of 37.75% and 31.67% respectively (ICES 2012).

5.1 Estimation of parameter values

To estimate the stock-recruitment relationship I use ICES data for the Norwegian coastal cod for the years 1984 to 2011 (ICES 2012). I estimate the logarithm of the Ricker stock-recruitment relationship of section 3, i.e.

$$\log(R_t) = \log(\hat{\alpha}ssb_t e^{\hat{\beta}ssb_t}) + \epsilon_t, \quad (17)$$

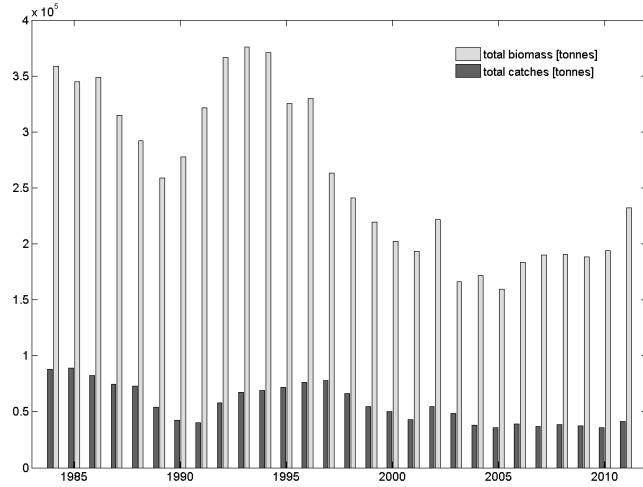


Figure 1: Norwegian coastal cod. Total stock biomass and total landings for the years 1884-2011.

where ϵ is a normally distributed random variable $N(0, \sigma^2)$. Nonlinear least square yield the following parameters $\hat{\alpha} = 0.4954$ with confidence interval $(0.28, 0.71)$, and $\hat{\beta} = 2.5833$ with $(-0.59, 5.76)$.

As illustrated in section 3, ocean acidification is likely to increase the density-independent mortality during the recruitment phase aT and thus to decrease α . The estimated α refer to the current pCO_2 level of $380\mu atm$. Frommel et al. (2012a) found that under the medium scenario of $1800\mu atm$ 12% of the larvae exhibit severe to lethal tissue damages, under the high scenario of $4200\mu atm$ this is the case for 75% of the larvae. Using my method from section 3 I can translate these data to $\alpha' = f^{-0.12}\alpha^{1.12}$ for the medium scenario and $\alpha'' = f^{-0.75}\alpha^{1.75}$ for the high scenario.

With the data I have it is not possible to estimate fecundity f and density-independent mortality a separately. I thus assume a fecundity parameter equal to one, such that the relation between α and α' (α'') simplifies to $\alpha' = \alpha^{1.12}$ ($\alpha'' = \alpha^{1.75}$). Note that, if f is below one α' will be lower, if f is above one α' will be higher than under my assumption. With the estimates for the control case

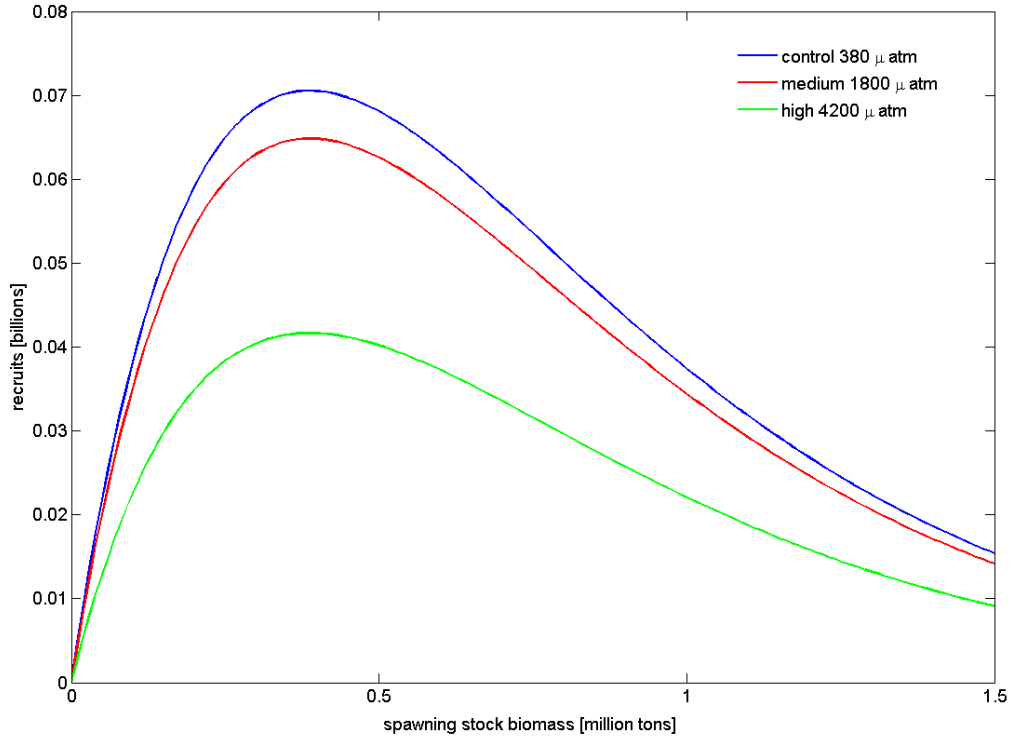


Figure 2: Influence of ocean acidification on the stock-recruitment relationship.

I thus get $\alpha' = 0.4554$ for the medium scenario and $\alpha'' = 0.2925$ for the high scenario. The resulting stock-recruitment curves are plotted in figure 2. As can be clearly seen, ocean acidification is likely to result in lower recruitment success given a certain spawning stock biomass.

For the other parameters, i.e. age-specific survival rate, weight at age and age specific maturity I also use ICES data and take the average over the years 1995 to 2011. The age-specific catchability I calculate with the help of the instantaneous age-specific fishing mortality rates F . I normalized the highest fishing mortality rate to one and determine the catchability of different age classes in relation to the catchability of this age class. The parameters are assembled in table 1.

For the cost structure of catching cod I refer to Richter et al. (2012), who have

²Since data for age class 1 is not available I approximated it by using the number of age class 2 and the natural mortality rate of 0.2, i.e. $19318 * e^{0.2}$

Age-class	Maturity	Weight	Catchability	Survival rate	Numbers
	m_a	w_a (kg)	ϕ_a	b_a	2011 [10^3]
1	0	0.078	0.00	$e^{-0.2}$	23595 ²
2	0	0.3628	0.01	$e^{-0.2}$	19318
3	0.02	0.9192	0.09	$e^{-0.2}$	14665
4	0.15	1.7325	0.32	$e^{-0.2}$	10541
5	0.45	2.4088	0.56	$e^{-0.2}$	6475
6	0.69	3.1853	0.77	$e^{-0.2}$	4471
7	0.87	4.3792	1	$e^{-0.2}$	2129
8	0.89	5.5797	0.9	$e^{-0.2}$	1295
9	0.96	7.1616	0.71	$e^{-0.2}$	693
10	0.98	10.5224	0.71	$e^{-0.2}$	941

Table 1: Parameters used in the age-structured fishery model

estimated the cost and demand structure of the Norwegian cod fishery for different vessel types. I use their estimation for the coastal vessels, since Norwegian coastal cod is mainly caught inside the fjords or offshore by smaller vessels. Richter et al. concentrated on the Northeast Arctic cod. But as already mentioned, when catching cod inside the 12 nautical mile zone both species cannot be distinguished. Thus, I assume a joint production of NEAC and NCC and apply the cost structure of Richter et al. (2012) to my model by replacing $H_t = h_{t,NCC} + h_{NEAC}$ and $X_t = X_{t,NCC} + X_{NEAC}$. While doing so, I assume that biomass and harvest rates of NEAC are fixed throughout the years. As a reference scenario I take the steady state values for harvest and biomass from Richter et al. (2012), which are $X_{NEAC}^* = 3.41$ million tons and $h_{NEAC}^* = 0.67$ million tons.

The production process of a vessel is described by a Cobb-Douglas harvest function, where the amount of cod harvested in a given year (H_t) is a function of the vessel's effective fishing effort (E_t) and the total amount of cod biomass (X_t),

i.e.

$$H_t = q X_t^\chi E_t^\gamma \quad (18)$$

$$(h_{t,NCC} + h_{NEAC}) = q (X_{t,NCC} + X_{NEAC})^\chi E_t^\gamma \quad (19)$$

Here, q is a catchability coefficient, χ is the stock-output elasticity and γ is the effort-output elasticity. Effort E_t is the number of days catching cod multiplied by the vessel's Gross Tonnage, i.e. effort is measured in efficiency units – tonnage days. Solving for effort yields $E_t = \left(\frac{(h_{t,NCC} + h_{NEAC})}{q (X_{t,NCC} + X_{NEAC})^\chi} \right)^{1/\gamma}$.

Regarding the cost of catching cod Richter et al. (2012) distinguish between fixed costs (k) and variable costs (v). Hence, the annual costs of a coastal vessel spending E tonnage days catching cod are given by

$$c_t = k + v E_t. \quad (20)$$

Combining equations (18) and (20) then yields

$$c_t = k + v \left(\frac{H_t}{q X_t^\chi} \right)^{1/\gamma} \quad (21)$$

$$c_t = k + v \left(\frac{(h_{t,NCC} + h_{NEAC})}{q (X_{t,NCC} + X_{t,NEAC})^\chi} \right)^{1/\gamma}. \quad (22)$$

With the parameter estimated by Richter et al. (2012) I have

$$c_t = 0.37 + 99.51 \left(\frac{(h_{t,NCC} + h_{NEAC})}{0.032 (X_{t,NCC} + X_{t,NEAC})^{0.41}} \right)^{1/0.79}. \quad (23)$$

For the demand function I assume a fixed price for NCC. Landings of NCC are small relative to those of NEAC, such that changes in landings of NCC will not change the price for cod. Following Richter et al. (2012) the average inflation-corrected ex-vessel price obtained for one kilogram of cod fish are 17.32 NOK for coastal vessels. Finally I assume that fishermen are risk averse with a coefficient of constant relative risk aversion of $\nu = 0.75$, see equation (13).

5.2 Results

I determine the optimal fishery management for three scenarios of ocean acidification: 1) the control scenario with $380\mu atm$, 2) a medium scenario with $1800\mu atm$

and 3) a high scenario with $4200\mu atm$. The optimal development of the harvest and the total stock for the three scenarios, given an interest rate of 2% or 10%, are shown in figures 3 and 4. In the control and medium scenario the optimal solution is an almost smooth path toward a constant population level. On the contrary I observe the tendency to pulse fishing in the high scenario, in particular for higher interest rates.

Given an interest rate of 2% the steady-state stock size equals 490,730 tons for the control scenario, 463,480 tons for the medium scenario and about 329,240 tons for the high scenario. The corresponding steady state harvest rates are 77,457 tons for the control, 69,806 tons for the medium scenario and about 37,573 tons for the high scenario. The difference in harvest possibilities relative to the control scenario is thus 7,651 tons in the medium scenario and 39,884 tons in the high scenario, which translates in an annual loss of 131 million NOK for the medium and 687 million NOK in the high scenario.

Given an interest rate of 10% I get a steady state stock size of 359,700 (327,330) tons and a steady state harvest rate of 68,700 (60,640) tons in the control (medium) scenario. But the optimal solution differs completely for the high scenario of ocean acidification. With pulse fishing the amount of harvest fluctuates heavily between 0 tons and 88,000 tons with an inter-annual average of about 27,000 tons. The average harvest is only 40% of the harvest in the control case, but the maximum harvest rates are much higher than the steady state values in the control and medium scenarios. At the same time the stock size decreases to an average of 160,000, tons which is less than the half of the steady state stock size in the control case.

Pulse fishing, or fishing heavily at regular intervals rather than continually, could occur as a consequence of unperfect selectivity in the fishing gear. It will also emerge whenever pulse fishing may produce higher yields than fishing constantly with a lower effort (Clark, 1990). In my example I observe pulse fishing under the extreme levels of ocean acidification and a relatively high interest rate of 10%. Although the main reason will supposedly lie in the non-selectivity of the fishing

gear, ocean acidification is likely to further destabilize the system. In particular pulse fishing could be fostered by the low recruitment success under extremely low pH-values. If the annual growth in terms of recruitment is very low, it could be more profitable to wait some years until the stock has accumulated rather than fishing a constant - but probably small - fraction of the fish stock every year.

My results also show that the impact of the interest rate is at least as strong as the effect of ocean acidification. The difference in optimal harvest between the two interest rates is as high as the respective difference between the control and medium scenario. Further, pulse fishing in the high scenario only occurs for a high interest rate of 10%. Thus, ocean acidification is only one determinant and in the short run less important than economic parameters like the interest rate.

6 Discussion

In this paper I examined how ocean acidification could influence the optimal fishery management. I have demonstrated how results from laboratory-based experiments could be scaled from physiological responses to population processes like the stock-recruitment relationship.

On the example of the Norwegian coastal cod I have shown, that decreasing pH-values under ocean acidification will most likely decrease the recruitment success and will thus result in a lower harvestable biomass and lower harvest rates. I could demonstrate that the consequences will be moderate under a scenario with $1800\mu atm$, predicted for the year 2300, but will be severe under an extreme coastal upwelling scenario of $4200\mu atm$. Under the medium scenario harvest will decrease by about 10% (12%) given an interest rate of 2% (10%), whereas the high scenario will result in 52% (60%) lower inter-annual average harvests. In addition I observed the tendency to pulse fishing in the high scenario under an interest rate of 10%.

Although my results show that ocean acidification could have negative effects on the harvestable biomass and thus on harvest possibilities, many questions still remain open: My analysis is restricted by the limited knowledge about the concrete

consequences of ocean acidification on the physiology of specific fish species. I assumed that decreasing pH-values have a detrimental effect on the recruitment of the fish stock. The negative effect on stock productivity might be enhanced by effects on the metabolism and thus on the growth of the fish stock (Cheung et al., 2012).

Beside these direct effects on the physiology of a fish species it could have indirect impacts via ecological interactions, such as alteration in the food web or habitat. For example, higher CO_2 -levels could increase the primary production and could thus increase the food supply which in turn could result in higher growth rates of some fish species (Le Quesne and Pinnegar, 2012). Furthermore, ocean acidification is only one component of multiple pressures like fishing, habitat modification, climate change, species introduction and nutrient enrichment and should be considered in this context as these pressures could have both interactive and cumulative impacts (Le Quesne and Pinnegar, 2012).

Another limitation of my studies is, that I could not examine the effects of ocean acidification in the short run. The underlying experimental data I used in my model starts with an already relatively high level of pCO_2 in ocean waters, i.e. $1800\mu atm$ as predicted for the year 2300. Data for intermediate levels are missing, but necessary to learn, which effects ocean acidification would have for the next 50-100 years (Denman et al., 2010).

In addition I didn't include possible evolutionary adjustment processes into my consideration (see also Cheung et al., 2011). Looking at the robustness of the Eastern Baltic cod with respect to even extreme levels of ocean acidification it is very likely, that other fish species are also able to adjust to higher CO_2 levels in the long run. “[L]aboratory-based experiments are limited in their ability to inform on potential for long-term adaptation to a pressure that gradually develops, the response of a few individuals exposed to an abrupt change over a few days or weeks may significantly differ from the response of individuals in a population that is exposed to gradually increasing acidification over decades or centuries” (Le Quesne and Pinnegar, 2012) It is thus not unlikely that the found effects of

decreased pH-values are highly overestimated and that actual effects will be less severe.

Hence, this paper is just a first step toward including experimental data on biological effects of ocean acidification into ecological-economic models. Further research will be needed, in particular on the ecosystem level, to get reliable results as a basis for adaptive fishery management under ongoing ocean acidification.

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Progress in Oceanography (107):61-79.

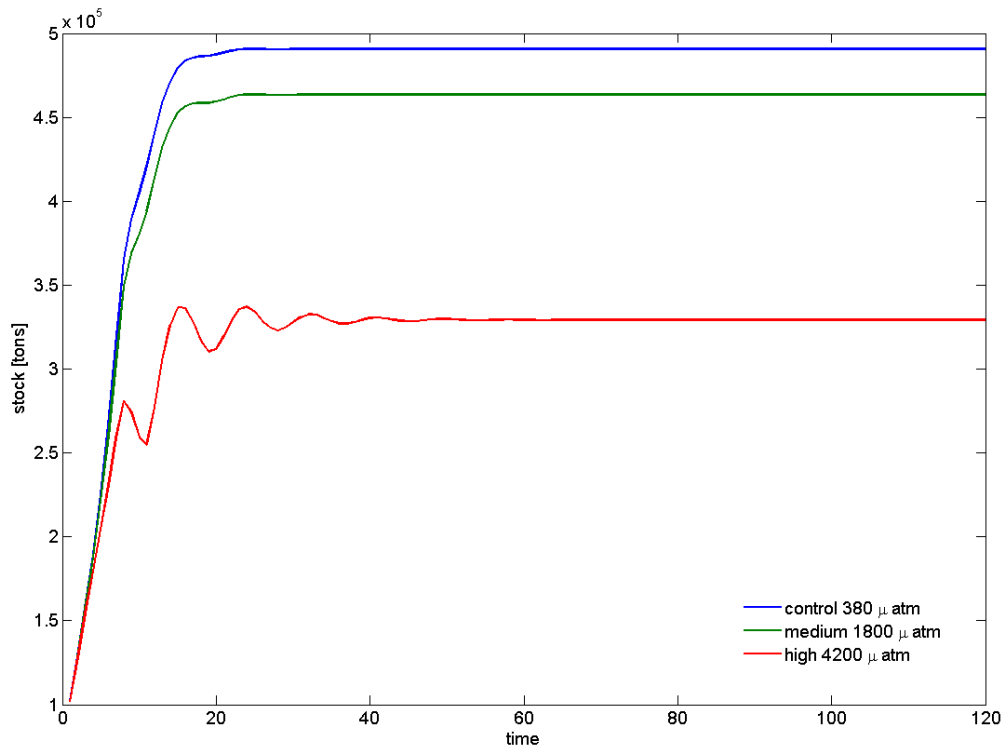
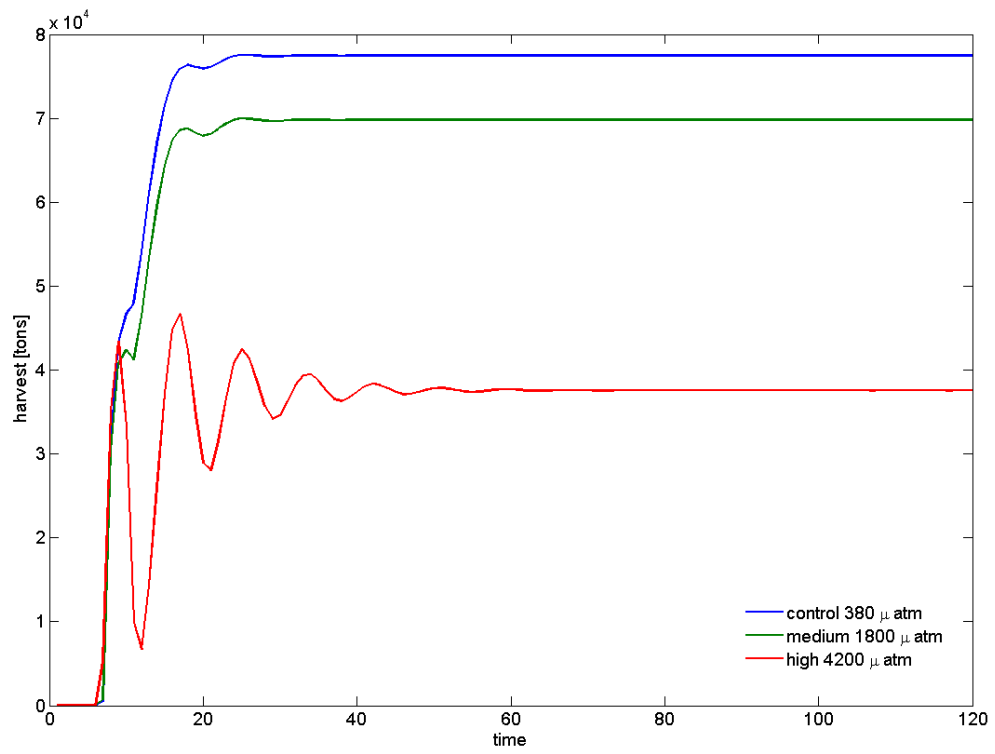


Figure 3: Optimal harvest and biomass under ocean acidification, given an interest rate of 2%.

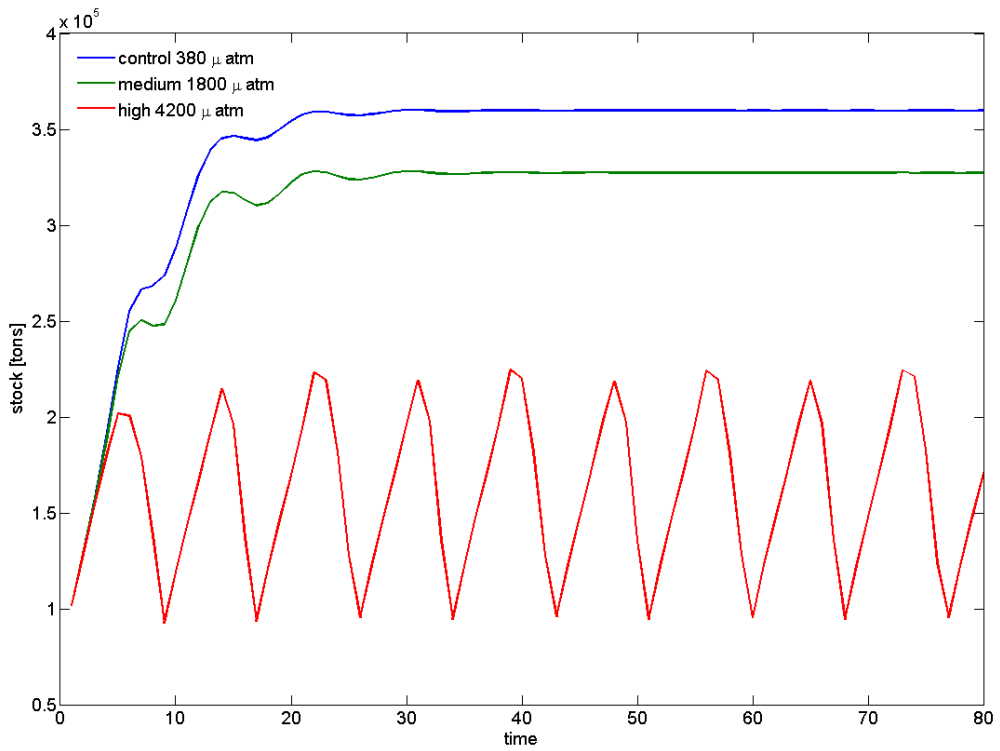
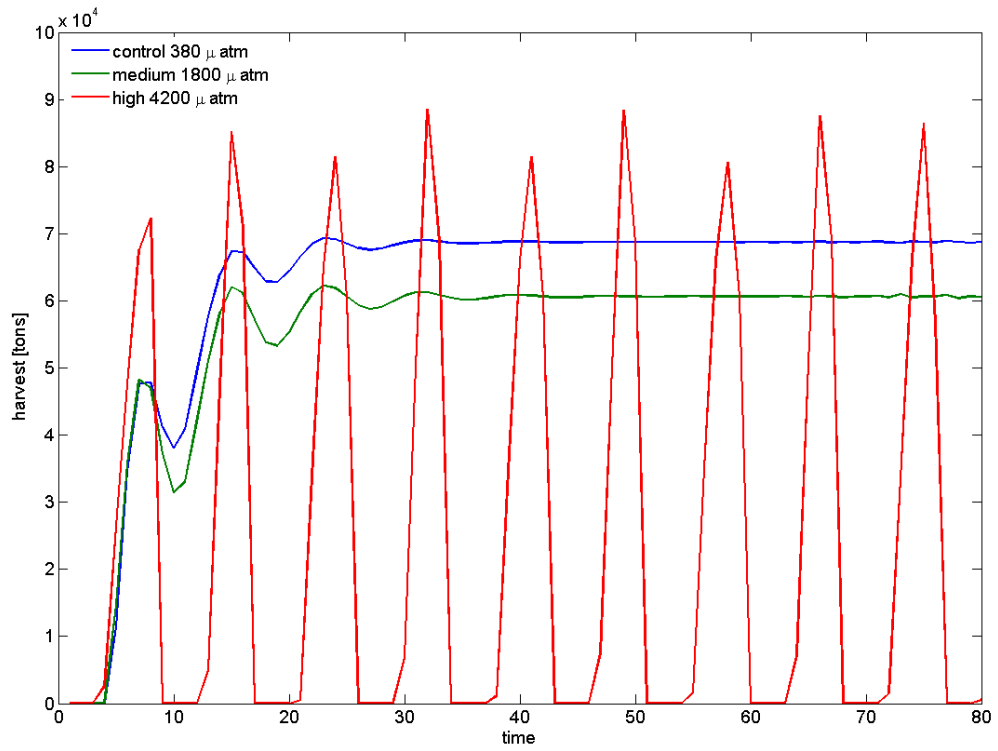


Figure 4: Optimal harvest and biomass under ocean acidification, given an interest rate of 10%.

Eidesstattliche Erklärung

Ich erkläre hiermit an Eides Statt, dass ich meine Doktorarbeit "Optimal fishery management under environmental uncertainty" selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

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| 01/2001-10/2005 | Angestellte im gehobenen Verwaltungsdienst im Landesamt für Natur
und Umwelt des Landes Schleswig-Holstein |
| 08/2000-12/2000 | Angestellte im gehobenen Verwaltungsdienst im Statistischen
Landesamt Schleswig-Holstein |