Greed is good: from super-harvest to recovery in a stochastic predator-prey system

BY Yuanming Ni, Leif K. Sandal, Sturla F. Kvamsdal and Diwakar Poudel

DISCUSSION PAPER

NHH

Institutt for foretaksøkonomi
Department of Business and Management Science

FOR 05/2019

ISSN: 1500-4066

September 2019

Greed is good: from super-harvest to recovery in a stochastic predator-prey system

Yuanming Ni [a], Leif K. Sandal [b], Sturla F. Kvamsdal [c], Diwakar Poudel [d]

Abstract

This paper demonstrates a predator-prey system of cod and capelin that confronts a possible scenario of prey extinction under the first-best policy in a stochastic world. We discover a novel 'super-harvest' phenomenon that the optimal harvest of the predator is even higher than the myopic policy, or the 'greedy solution', on part of the state space. This intrinsic attempt to harvest more predator to protect the prey is a critical evidence supporting the idea behind 'greed is good'.

We ban prey harvest and increase predator harvest in a designated state space area based on the optimal policy. Three heuristic recovery plans are generated following this principle. We employ stochastic simulations to analyse the probability of prey recovery and evaluate corresponding costs in terms of value loss percentage.

We find that the alternative policies enhance prey recovery rates mostly around the area of 50% recovery probability under the optimal policy. When we scale up the predator harvest by 1.5, the prey recovery rate escalates for as much as 28% at a cost of 5% value loss. We establish two strategies: modest deviation from the optimal on a large area or intense measure on a small area. It seems more cost-effective to target the stock space with accuracy than to simply boost predator harvest when the aim is to achieve remarkable improvement of prey recovery probability.

Keywords: stock recovery, resilience, predator-prey, ecosystem, stochastic

[a] Norwegian School of Economics. Helleveien 30, 5045 Bergen, Norway. Ni.yuanming@gmail.com

[b] Norwegian School of Economics. Helleveien 30, 5045 Bergen, Norway. Leif.Sandal@nhh.no

[c] SNF – Centre for Applied Research at NHH. Helleveien 30, N-5045 Bergen, Norway

[d] Norwegian Polar Institute. Fram Center, Pb. 6606 Langnes, N-9296 Tromsø, Norway

1. Introduction

Marine fisheries are vital resources for human society and ecosystem, especially with growing world population and increasing food demands (FAO, 2008). The current progress towards sustainable fisheries is at an insufficient rate and the stock recovery is generally overwhelmed by unsustainable fishing practices (Teh, Cheung, Christensen, & Sumaila, 2017). To improve the current fisheries management requires an effort to address both the direct economic gains and the indirect ecological values of the resource. To assess the existence value and the risk of extinction of any species, it is more realistic to include dynamic stock interactions from an ecosystem perspective. Feasible management practices that aim to rebuild a weak stock in a system should be evaluated with regards to its effects and costs.

With widely recognized depletion of various global fisheries and increasing climate uncertainty, many researchers and policy makers have prioritized their focus to sustainability, stock recovery and collapse. Incorporating sustainability considerations adds additional layers of complexity to conventional models (Howarth, 1995). Woodward & Bishop (1999) included a sustainability constraint in their model to suggest long-term sustainable management in a deterministic setting. Kama & Schubert (2004) chose to derive decision rules of a sustainable development under a special case of preference uncertainty. Britten, Dowd, Kanary, & Worm (2017) revealed how a changing environmental context can reform the recovery timeline and delay the rebuilding of depleted fish stocks. Rosa, Vaz, Mota, & Silva (2018) developed an age-structured model where the objective function incorporates the risk of fishery collapse, in addition to profit maximization and fishers' preference for stable landings. They managed to illustrate that their framework assists the analysis and design of harvest control rules. Diwakar Poudel, Sandal, & Kvamsdal (2015) discovered that the risk of stock collapse due to stochastically induced critical depensation increases with stochasticity in a single species model.

Healthy and diverse marine ecosystems are essential in order to ensure they are resilient to inevitable shocks and stresses. It has become clear that ecosystem-based fisheries management (EBFM) is a desired approach towards resilient fisheries (Link et al., 2012). In contrast to treating different species individually and separately, an ecosystem-based approach deals with the interacting components in a systematic and dynamic way. The most common models of single species ignores the ecological as well as the technological and economic interactions among species (Kasperski, 2010). This may lead to misleading results and incorrect policy decisions causing over or under exploitation of the stocks (Fleming & Alexander, 2002; Maravelias, Damalas, Ulrich, Katsanevakis, & Hoff, 2011). Usually the economic interactions play an important role in generating the overall harvesting pressure on the commercially valuable species.

Multispecies models in the literature have been attempts to account for ecosystem concerns. Earlier multispecies studies focused mainly on a predator-prey relationship from different trophic levels (May, Beddington, Clark, Holt, & Laws, 1979; Yodzis, 1994). However, they merely addressed the biological yields without considering the economic aspects of harvesting. Later, some suggested deterministic bioeconomic models with an optimal equilibrium solution (Fleming & Alexander, 2002; Kar & Chaudhuri, 2004). They found it difficult to solve for the optimal paths even with linear objective functions. Some concluded that multispecies management provides distinct advantages allowing for more realistic modelling of growth rates and better understanding of fish population dynamics (Hollowed et al., 2000). Nonetheless, multispecies bioeconomic models are limited due to unavailability of the analytical solutions (Posch & Trimborn, 2010) and computational difficulties (Singh, Weninger, & Doyle, 2006).

Most multispecies bioeconomic studies propose optimal harvesting in a deterministic setting (Clark, 2010; Woodward & Bishop, 1999; Sandal & Steinshamn, 2010). However, most of the economic and biological processes take place in an uncertain environment in reality (Charles & Munro, 1985). Uncertainties in fishery include stock measurement error, parameter estimation errors, environmental variability influencing the growth of fish stocks, structural uncertainty and model error (Charles, 1998; Sethi, Costello, Fisher, Hanemann, & Karp, 2005; Nøstbakken & Conrad, 2007; Roughgarden & Smith, 1996; Poudel, Sandal, & Kvamsdal, 2015; Kvamsdal, Poudel, & Sandal, 2016). Most of the extant literature that evaluates long-term stock management does not consider such uncertainties sufficiently. Stochastic models with a single species have gained popularity over the years (Clark & Kirkwood, 1986; Hannesson, 1987; Sandal & Steinshamn, 2017; Sethi et al., 2005; Singh et al., 2006; Kugarajh, Sandal, & Berge, 2006; Bruce, J, & Christopher, 2009), but stochastic multispecies models are still uncommon in the literature (Agnarsson et al., 2008).

We employ a feedback policy approach where the optimal control (harvest) is a direct function of the state variable (stock). Instead of the commonly used time paths approach, the feedback approach is superior when faced with uncertainty (Agnarsson et al., 2008). We also apply the DP (Dynamic Programming) technique, conducting value and policy iterations to solve for the optimal policy and value (Judd, 1998). The DP approach is a useful method when considering the multispecies management model under stochasticity (Sanchirico & Springborn, 2011).

This study is inspired by previous work of Sandal & Steinshamn (2010). In this paper, we work with a continuous-time stochastic multispecies predator-prey bioeconomic model. Based on the optimal policy derived from the numerical solution of a predator-prey system, we generate alternative harvesting policies in search for recovery of the less valuable prey stock. We conduct simulations to investigate the probability of prey recovery in a certain period of time, which also mirrors the risk of prey collapse. We progressively refine the recovery plans using three heuristics to explore the consequential benefits and costs. Using the DP technique, we evaluate the costs of implementing the alternative policies, providing references for the existence value of the prey species. We introduce the concept of value elasticity of recovery, which sheds light on a possible state-dependent recovery approach for further research.

2. Predator-prey system

2.1 Model

We employ a continuous-time predator-prey bioeconomic model. The general interdependent deterministic biological growth model is similar to those of Clark (1990), Agnarsson et al. (2008) and Poudel et al. (2012). Letting x be the prey species state and y be the predator stock state, the continuous-time deterministic growth increments of the system are:

$$\begin{aligned} dx &= [f(x,y) - u_x]dt \\ dy &= [g(x,y) - u_y]dt \end{aligned} \tag{1}$$

Functions $f(x,y)$ and $g(x,y)$ are the biological growth functions of the prey and predator respectively, while u_i stands for the harvest rate of species $(i = x, y)$. The term dt is the time increment. Furthermore, a two-species interaction model with stochastic dynamics is generated by adding volatility terms in equation (1) in the following way:

$$\begin{pmatrix} dx \\ dy \end{pmatrix} = F(x,y,u_x,u_y)dt + \sigma(x,y) \begin{pmatrix} dB_x \\ dB_y \end{pmatrix} \tag{2}$$

where $F(x,y,u_x,u_y) = \begin{pmatrix} f(x,y) - u_x \\ g(x,y) - u_y \end{pmatrix}$ and $\sigma(x,y) = \begin{pmatrix} \sigma_{11}x & \sigma_{12}y \\ \sigma_{21}x & \sigma_{22}y \end{pmatrix}$.

It can formally be considered as the two-dimensional controlled *Ito-process*: $dZ = F(Z,u) + \sigma(Z)dB$. In equation (2), term $\sigma(x,y)$ is the diffusion matrix, and dB_x and dB_y denote the incremental basic Brownian motion, which is independent and identically distributed (*i.i.d.*) with mean zero and variance dt. The additive noise formulation is a general Wiener process and contains the multiplicative case (Poudel et al., 2015; Kvamsdal et al., 2016). We assume the stock biomass states and harvests to be nonnegative.

The economic part of the model consists of the net revenues from harvesting both species, which can be obtained by adding revenue from each stock.[1] Let $\pi\left(x, y, u_x, u_y\right)$ be the total net revenue, where $\pi_x\ (x, u_x)$ and $\pi_y\ \left(y, u_y\right)$ are the revenues from x and y respectively:

$$\pi\left(x, y, u_x, u_y\right) = \pi_x\ (x, u_x) + \pi_y\ \left(y, u_y\right) \tag{3}$$

$$= p_x(u_x)u_x - c_x(x, u_x) + p_y\left(u_y\right)u_y - c_y\left(y, u_y\right)$$

where $p_i(\cdot)$ and $c_i(\cdot)$ are inverse demand functions and cost functions respectively. We assume that the objective of the fisheries management authority (such as a regional fisheries management organization that acts as the sole owner of the resource) is to maximize the expected net present value (NPV) of harvesting activities of the fishery over an infinite time horizon. This can be achieved by maximizing the following functional with respect to the policy or control variable u_i.

$$J\left(x, y, u_x, u_y\right) = E\left[\int_0^{\infty} e^{-\delta t}\, \pi\left(x, y, u_x, u_y\right) dt\right] \tag{4}$$

The nonnegative parameter δ is the discount rate, and E is the expectation operator. The value function and the optimal policy can be obtained by solving the Hamilton-Jacobi-Bellman (HJB) equation:

$$\delta V(x, y) = \max_{u \in U \subset R_+^2} \{\pi(x, y, u_x, u_y) + DV^T(x, y)F\left(x, y, u_x, u_y\right) \tag{5}$$

$$+ \frac{1}{2} tr[\sigma(x, y)\sigma^T(x, y)D^2V(x, y)]\}$$

where $DV(x, y) = \begin{pmatrix} \frac{\partial}{\partial x}V(x, y) \\ \frac{\partial}{\partial y}V(x, y) \end{pmatrix}$ and $D^2V(x, y) = \begin{pmatrix} \frac{\partial^2}{\partial x^2}V(x, y) & \frac{\partial^2}{\partial x \partial y}V(x, y) \\ \frac{\partial^2}{\partial y \partial x}V(x, y) & \frac{\partial^2}{\partial y^2}V(x, y) \end{pmatrix}$.

Closed-form solutions are usually rare because of the difficulty in solving the HJB equation given nonlinearity and boundary conditions. The Markov chain approximation approach is one of the most effective numerical methods for such problems with nonlinear control. The numerical optimization results will be presented in section 2.3. The solution procedure will not be emphasized with details in this paper.

2.2 Numerical specifications

[1]We assume that there is no market interactions between the demand for and prices of the two species. Therefore, the revenues from both species are added together.

The diversified ecosystem in the Barents Sea harbours two key fish species, namely capelin (*Mallotus villosus*), a plankton feeder, and Northeast Arctic cod (*Gadus morhua*), the main predator of capelin. Cod is considered the main resource of the Norwegian commercial white fish industry (Kugarajh et al., 2006), while capelin is the largest pelagic stock in the Barents Sea and potentially the most abundant in the world. The relationship between cod and capelin is highly dynamic in the Barents Sea ecosystem (Bogstad et al. 1997). As the prey, capelin is crucial for the growth of juvenile cod (Dalpadado & Bogstad, 2004). The cod recruitment and survival rate are directly affected by climatic conditions and availability of food. Higher temperature during spawning and more capelin have a positive effect on cod recruitment (Hjermann et al., 2007). Given various kinds of uncertainties in the Barents Sea ecosystem (Flaaten et al., 1998), we apply a stochastic multispecies model consisting of cod and capelin as the interacting predator and prey species.

Functional forms of the biological and economic components of the model, as well as the specifications of parameter values are based on the works of Agnarsson et al. (2008) and Sandal & Steinshamn (2010). Built on empirical data and analysis from existing work, our model ensures that the functional forms are relevant and the parameter values occupy a realistic part of the parameter space. We assume that a single authority who seeks to maximize the joint benefit of the predator-prey system manages both stocks. The upper bounds for the state space is $xmax = 10000$ and $ymax = 12000$. We set 100 grid points along each dimension of the state space to discretize the problem numerically. The biological growth functions of capelin (prey *x*) and cod (predator *y*) in equation (1) are specified as:

$$\begin{aligned} f(x,y) &= a_1x^2 - a_2x^3 - a_3xy \\ g(x,y) &= b_1y^2 - b_2y^4 + b_3xy \end{aligned} \tag{6}$$

where $a_1, a_2, a_3, b_1, b_2,$ and b_3 are parameters. The first two terms in equation (6) for each species represent the biomass growth in the absence of the other species and hence stand for the aggregated effects of the rest of the ecosystem. The xy-term represents the interactions between the two stocks. The numerical specification goes as follows[2]:

$$\begin{aligned} f(x,y) &= 1.8 \cdot 10^{-4}x^2 - 1.19 \cdot 10^{-8}x^3 - 2.1 \cdot 10^{-4}xy \quad (10^6 kg/year) \\ g(x,y) &= 2.2 \cdot 10^{-4}y^2 - 3.49 \cdot 10^{-11}y^4 + 1.82 \cdot 10^{-5}xy \quad (10^6 kg/year) \end{aligned} \tag{7}$$

The volatility of each species is assumed to be a linear function of its own stock level. It is also

[2] The value of parameter a_1 is $1.8 \cdot 10^{-3}$ on the referred papers, which is supposedly a typo.

assumed that there is no correlation between the stochastic terms. The diffusion matrix is thus specified as: $\sigma_{11} = 0.2$; $\sigma_{12} = 0$; $\sigma_{21} = 0$ and $\sigma_{22} = 0.2$.

The functional forms of the economic part in equation (3) are specified as follows:

$$\begin{aligned} p_x(u_x) &= p_1 \\ c_x(x, u_x) &= q_1 {u_x}^{\alpha_1} \\ p_y(u_y) &= p_2 - p_3 u_y \\ c_y(y, u_y) &= \frac{q_2 {u_y}^{\alpha_2}}{y} \end{aligned} \quad (8)$$

where $p_1, q_1, \alpha_1, p_2, q_2, \alpha_{1,}\alpha_2$, and p_3 are price, cost, and elasticity parameters. We assume that capelin is an unevenly distributed schooling species and the unit cost of harvesting is independent of its stock level. The simplified revenue function can be rewritten as:

$$\pi\left(y, u_x, u_y\right) = p_1 u_x - q_1 {u_x}^{\alpha_1} + p_2 u_y - p_3 u_y^2 - \frac{q_2 {u_y}^{\alpha_2}}{y} \quad (9)$$

The corresponding numerical specification is:

$$\pi\left(y, u_x, u_y\right) = u_x - 0.07 u_x^{1.4} + 12.65 u_y - 0.00893 u_y^2 - 5848.1 \frac{u_y}{y} \quad (10^6 NOK) \quad (10)$$

It is also worth mentioning that both stocks have commercial value but the predator is much more worthy in the market. The unit price of cod is 12.65 NOK/kg while that of capelin is 1NOK/kg. The optimal feedback solutions are calculated with a 5% discount rate *($\delta = 0.05$).*

2.3 Evidences for heuristics from the optimal policy

We interpret the optimal harvests from the point of view of how the first-best policy determines the development of the prey species capelin. As shown by the blue dashed lines in Fig.1, in a deterministic world, some initial states end up with capelin extinction while some others go to the other extreme of capelin prosperity. It seems that a slight change in the starting point could give rise to drastic differences of capelin stock development. In a single species setting, both stocks are sustainable on its own. The coexistence of two stocks in a predator-prey relationship gives rise to a possibility that the prey may disappear.

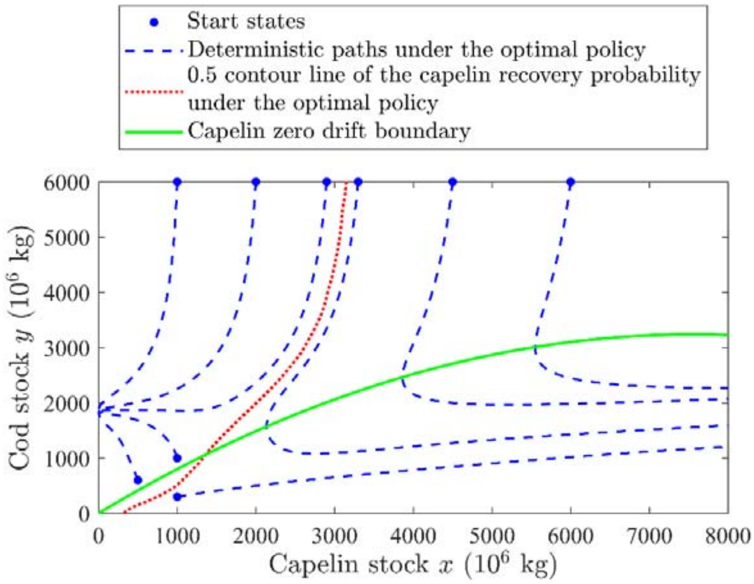

Fig 1. Development paths from various initial states

If capelin disappears, we lose the direct revenues from harvesting capelin as a commercial species as well as the indirect revenues due to a weaker cod stock. The risk of capelin collapse is embedded in the optimization model and the way that the optimal policy deals with this possibility is reflected in itself. We observe that the optimal harvest of both species expresses some level of intentional 'prey protection and recovery' strategy.

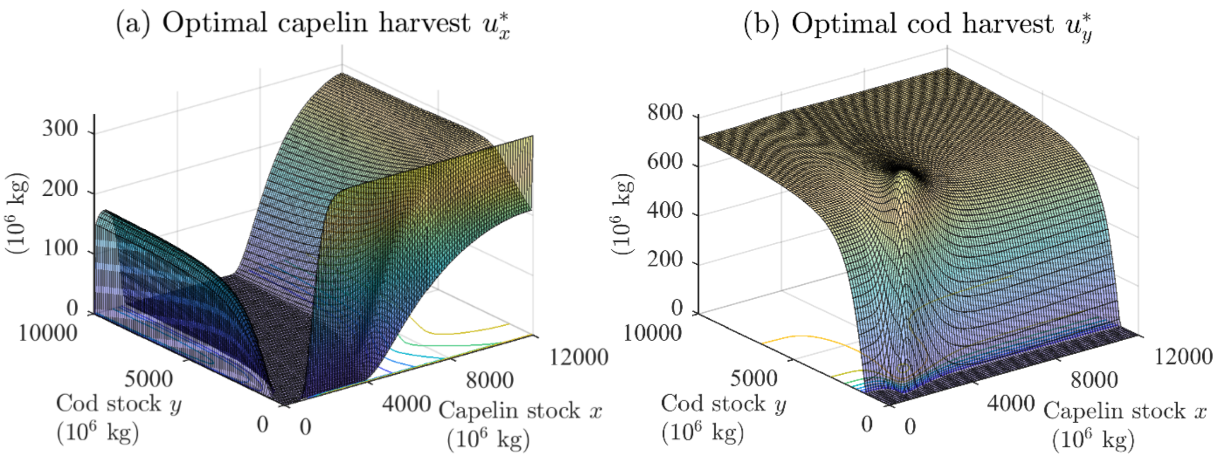

Fig 2. Optimal harvest for (a) capelin u_x^* and (b) cod u_y^*

The first evidence is the moratorium region or the 'valley' phenomenon in the optimal capelin harvest as shown in Fig. 2(a) with a surface plot of the harvest and in Fig. 3(a) with a contour plot of the harvest. When capelin stock is low, for example below $2000{\cdot}10^6$kg, it will most likely go extinct due to predation no matter how much human harvests. Therefore, the optimal capelin harvest is positive in this region in order to take advantage of whatever value that can still be acquired. Inside the moratorium area, i.e. bottom of the 'valley', the optimal policy equals zero, seeking to avoid capelin from disappearing or to slow down the extinction process. The conservation of capelin is stronger in the presence of higher volatility because a more stochastic cod stock intuitively requires more abundant food resource (Poudel et al., 2014).

The second evidence is that on part of the state space the optimal cod harvest exceeds the myopic cod harvest, forming what we call a 'super-harvest' phenomenon. The myopic or 'greedy' solution to the optimization model only takes into account a single period when calculating the profit function. We solve for the myopic harvests by maximizing $e^{-\delta}\pi\left(x, y, u_x, u_y\right)$ with respect to u_x and u_y. The results are displayed in Appendix Fig. B. Usually the greedy harvest is, as the name implies, larger than the optimal policy. Therefore, it is very novel and counterintuitive to observe an obvious bump in Fig. 2(b) and a significant state space area of the super-harvest in Fig. 3(b). Inside the 0 contour line in Fig. 3(b), the positive difference numbers together with the purple colours indicate how much the optimal harvest is even greedier than the greedy solution.

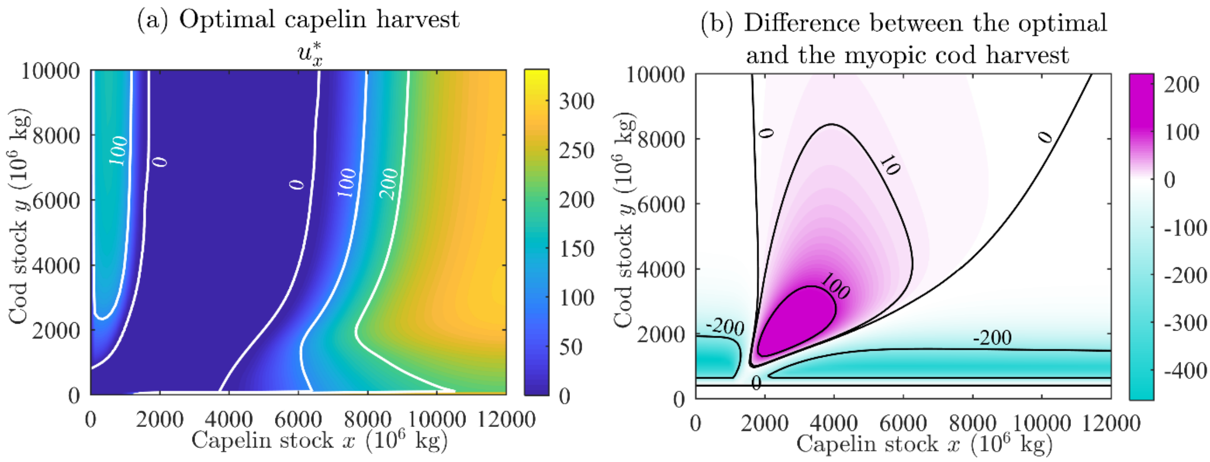

Fig 3. (a) Contour plot of the optimal capelin harvest u_x^*; (b) Contour plot of the difference between the optimal cod harvest u_y^* and the myopic cod harvest

Referring to the green line of capelin zero drift boundary as shown in Fig. 1, one possible explanation is that it is optimal to harvest a bit more cod so that the cod state shrinks at a faster speed. This enhances the probability that the states enter the area of positive capelin growth and land on the safe side for capelin. When cod is abundant, the speed-up effect could accumulate for a long time as cod transits from high to low. Thus, a low level of super-harvest applies to most of the cod abundant region. The optimal cod harvest bump (dark purple region in Fig. 3(b)) is probably where the system would extract the most potential. Given that the super-harvest emerges naturally and intrinsically with the optimal policy, the message is that it is worthy to give up some short-term revenues from the predator if the prey has a higher probability of long-term recovery. There is no additional existence value of the prey in the objective function and super-harvest does not appear when there is only one species.

The strategy of prey protection and recovery manifested in the optimal policy could be amplified when the non-economic values of the system are accommodated as well. In this work, we follow the two evidences analysed above, establish alternative polices according to various heuristics and evaluate the recovery plans concerning effects and costs.

We define A on the state space as the area in which the recovery plan replaces the optimal policy. The first evidence, i.e. moratorium of the optimal capelin harvest, is an intuitive and straightforward strategy. Following this, we set all capelin harvest to zero in A for all recovery plans. Due to the large area of moratorium in Fig. 3(a), some alternative harvests may result in no change for capelin policy. The second evidence, i.e. super-harvest of the optimal cod policy, is an active and more aggressive approach where the system chooses to be 'merciful' to the prey by being 'greedy' to the predator. Parameter θ ($\theta > 1$) describes the degree of deviation of the alternative cod harvest from the optimal cod harvest in A. The higher θ gets, the bigger existence value we bestow implicitly to the prey species.

2.4 Simulation settings

In order to evaluate the effect of a recovery plan, we look at the probability of capelin recovery and the improvement achieved by implementing the alternative policy instead of the optimal. We conduct Monte Carlo simulations with a feedback policy. To imitate a continuous-time Markov process, we apply a time unit of one year and a time step *dt* of 0.01 with 2000 periods, which leads to a simulated time horizon of 20 years. For each initial state, we simulate 2000 realizations and then calculate the corresponding probabilities. A trajectory is counted as capelin recovery if x exceeds or equals to $4000 \cdot 10^6$kg in the end of the simulation period. Similarly, a trajectory is considered capelin collapse if x ends up smaller than $120 \cdot 10^6$kg. The sum of capelin recovery and collapse probabilities equals one on most of the state space. We therefore conclude that 20 years is a long enough simulation period for most states to settle down either as capelin recovery or collapse.

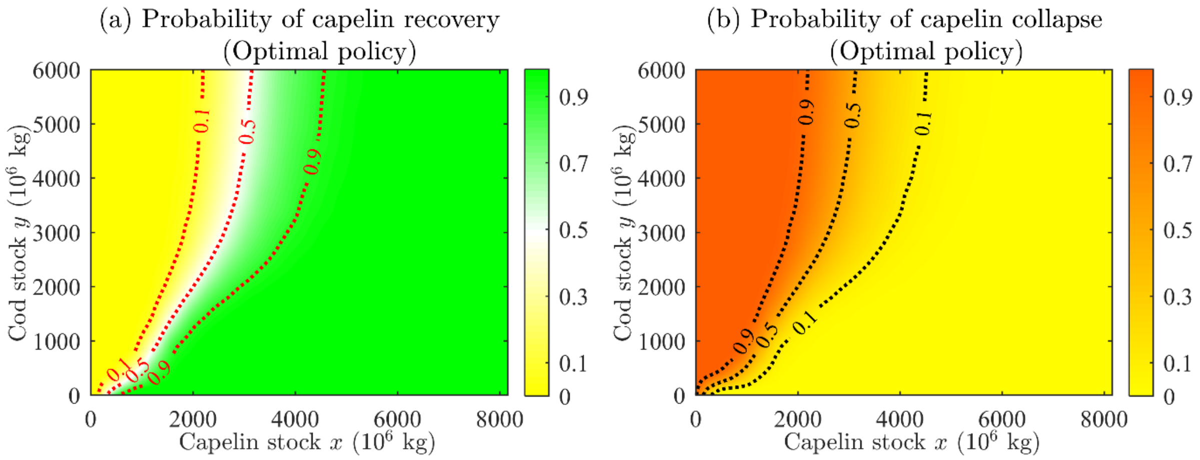

Fig 4. Contour plots of the probability of (a) capelin recovery and (b) capelin collapse

As shown in Fig. 4, the contour lines for both figures extend more and more vertically as cod stock increases, offering limited new information. In addition, the investigation interest shrinks as capelin becomes more and more plentiful. Thus, when presenting the results we focus on the state space area where cod stock y is smaller than $6000 \cdot 10^6$kg and capelin stock x is smaller than $8000 \cdot 10^6$kg. A total of 100 points from a 10-by-10 even grid are chosen as the initial states for the simulations. The results are then transferred onto the fine grid of the state space using cubic interpolation.

In Fig. 4(a), less than 10% of realizations end up as recovered for states within the area to the left of the 0.1 contour line. More than 90% of realizations are considered as capelin recovery for states within the area to the right of the 0.9 contour line. Similar conclusions could be drawn from the probability map of capelin collapse in Fig. 4(b). The risk of prey extinction is highly mirrored to the probability of prey recovery. Therefore, we focus on presenting and interpreting the results of capelin recovery in the rest of the paper.

3. The Simple Heuristic (SH)

3.1 Recovery plan of SH

The objective of all the recovery plans is to decrease the risk of capelin extinction and to promote the sustainability and resilience of the predator-prey system while considering the cost and practicality of the alternative policy. Following the two evidences in section 2.3, the recovery plan of Simple Heuristic (SH) is generated out of plain intuitions. We ban the prey harvest and increase the predator harvest on area A^{SH} where both stocks coexist and the prey is considered weak. For capelin stocks lager than $4000 \cdot 10^6$kg, the likelihood of capelin recovery is already very high. Deviation from the optimal policy is deemed unnecessary in this case.

Therefore, the area, as shown in Fig.5, is defined as $A^{SH} = x \in (0,4000] \cap y \in (0, ymax]$. The alternative harvest is calculated as follows:

$$\begin{aligned} u'_x(x,y) &= 0 \\ u'_y(x,y) &= u^*_y(x,y) \cdot \theta \end{aligned} \tag{11}$$

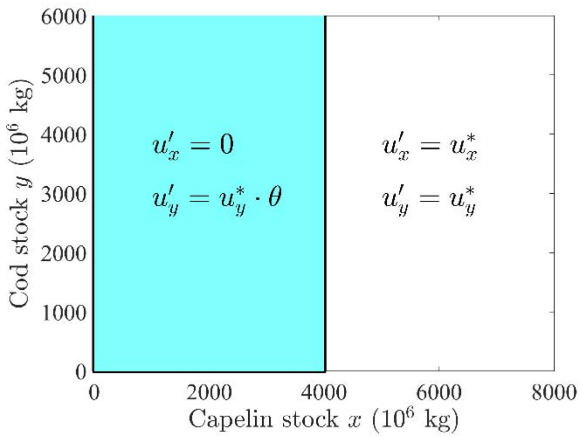

Fig 5. State space area A^{SH}(blue colored) and corresponding policy of the Simple Heuristic (SH) recovery plan for capelin and cod

Harvesting the predator in a greedy manner has its practicality when it comes to implementation of the recovery policy. Taking more predator not only helps to recover the prey but also imposes no pressure regarding extra monetary investment. Putting more cod on the market lowers the total profit according to the objective function, but it can be positive for the local labour market as well such as the processing companies. In addition, raising the quota of a valuable commercial species is unlikely to confront strong opposition from fishers. Sandal & Steinshamn (2010) have investigated the possibility of rescuing the prey by harvesting the predator. In this paper, we focus on the probabilistic evaluation of the recovery plan together with the corresponding cost.

3.2. Evaluation of SH

We employ two values of parameter θ, i.e. 1.2 and 1.5, and demonstrate on the state space the probability of capelin recovery, the improvement of the probability by the recovery plan and the value loss for diverging from the optimal policy.

We plot the contour lines of capelin recovery probability under the optimal policy (see Fig. 4(a)) as a reference using red dotted lines. As illustrated in Fig. 6(a,b), harvesting more predator than the optimal cod policy increases the likelihood of capelin recovery and pushes the blue dashed contour lines to the left. When θ takes the higher value of 1.5, the shift towards left is more obvious. The two styles of contour lines merge where cod state lies within the moratorium region. In the moratorium area, cod harvest remains zero no matter what value θ takes.

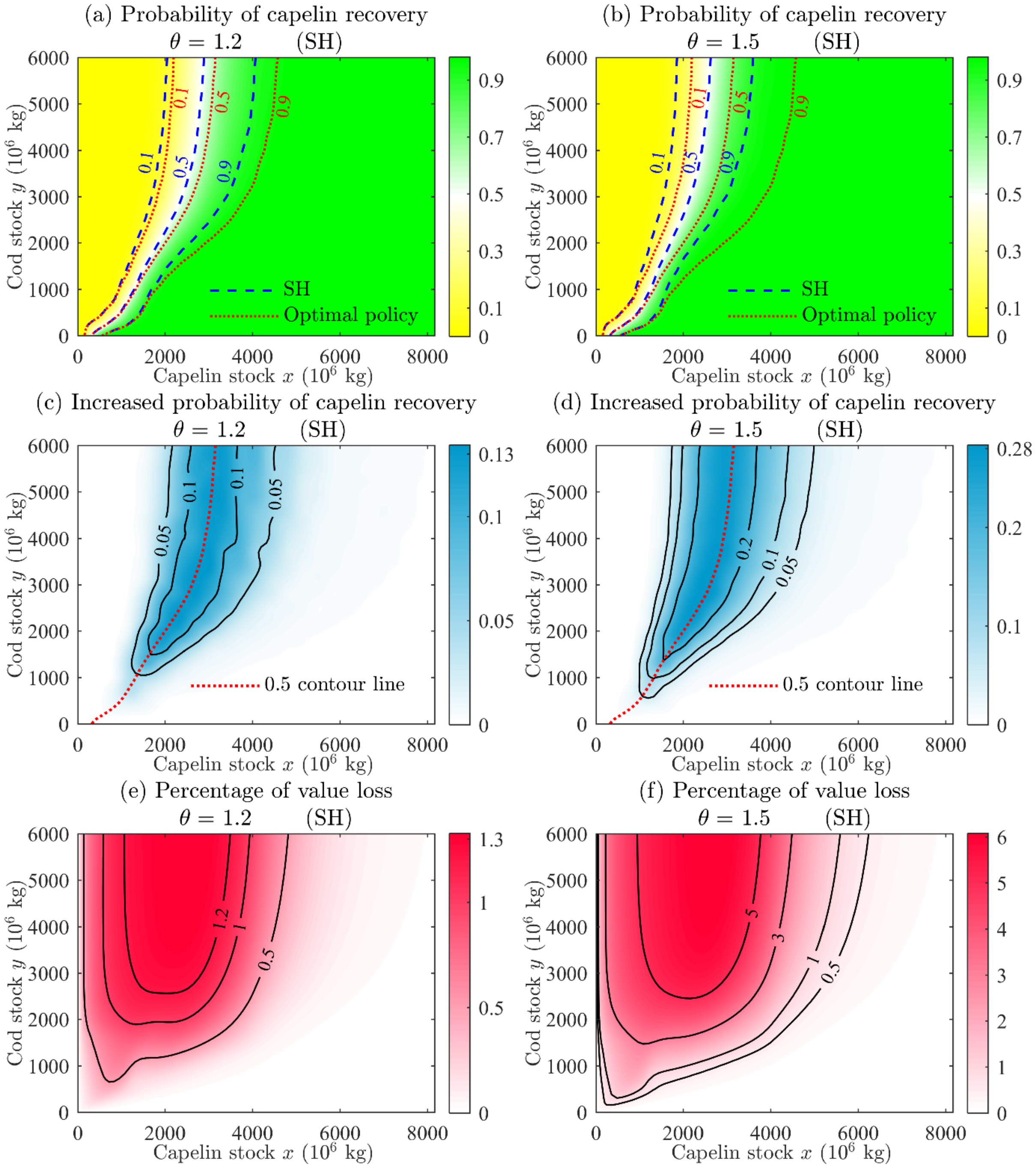

Fig 6. Recovery plan of Simple Heuristic (SH) with $\theta = 1.2$ and $\theta = 1.5$: (a,b) Probability of capelin recovery; (c,d) Increased probability of capelin recovery; (e,f) Percentage of value loss compared with the optimal value

In order to describe the performance of the recovery plan, we present the difference of capelin recovery probability between the alternative and the optimal policy. From Fig. 6(c,d), we observe that the enhancement is most evident on the narrow blue area within the 0.05 contour line, which wraps around the red dotted 0.5 contour line of capelin recovery rate under the optimal policy. Comparing with the marked areas in Fig. 3, where the optimal policy intends to rescue the prey in search for extracting the most value, the blue areas fall inside of the moratorium region in Fig. 3(a) and coincides with the super-harvest area to a large extent.

When $\theta = 1.2$, the most effective case is for the recovery rate to rise from around 50% to 63%, leading to a maximum improvement of 13% in the darkest blue part. When $\theta = 1.5$, the most fruitful case is for the recovery probability to escalate from around 50% to 78%, which is rather prominent. The improvement looks rather trivial and negligible outside of the 0.05 contour lines. It is either because capelin stock is doomed to go extinct when the predator is strong and the prey is weak or because capelin species is quite safe already even without the extra harvest on cod.

Note that the approach of calculating recovery probabilities automatically leaves out some special situations. For example, a state may begin by developing into capelin collapse and then shift towards the safe equilibrium thanks to a weakening cod stock. But 20 years of simulation period is not long enough for it to be considered as recovered. Therefore, the boost in capelin recovery rate exposes only a part of all the effects produced by the recovery plan. For some states that are outside of and close to area A^{SH}, the likelihood of ending up with a recovered capelin stock also grows. Although the alternative harvest has a sharp change on the boundary, the impact distributes more progressively.

Corresponding to the benefit of the recovery plan, the other side of the coin is the incurred cost related to implementing the alternative instead of the optimal policy. By applying the value iteration DP technique, we are able to solve for the value function of a given policy. The amount of value difference between the alternative and the optimal harvest is the value loss in absolute terms.

The percentage of value loss, manifested in Fig. 6(e,f), is the percentage number of the value loss compared to the optimal value function. When $\theta = 1.2$, the worst case is that the recovery plan costs 1.3% of the optimal value. When $\theta = 1.5$, the alternative harvest could result in a value loss of as much as 6% of the optimal value. While the capelin recovery probability increment is approximately linear to the excessive cod harvest, the percentage of value loss is more sensitive to the change in alternative policy.

All the states that suffer from value losses spread fairly widely on the stock space. While it is definitive that the states inside A^{SH}, except for the moratorium region, are subjected to value losses due to deviation from the optimal policy, it is less obvious for the states outside. Keep in mind that the value of each state is the sum of the expected and discounted profits in an infinite time horizon. In a stochastic world, as long as there exists a possibility for a state outside A^{SH} to enter the area of inevitable value losses at some point, the total value will be lower than the optimal no matter how long the state stays inside of A^{SH}. Therefore, as cod stock enlarges, the predator is able to bring down capelin faster and drag the state deeper inside of A^{SH}, which provokes a heavier value loss. As a result, we can clearly observe that the contour lines from Fig. 6(f) form an asymmetric 'U' shape leaning towards the right.

The approach of solving the value function for a recovery plan and then obtaining the value loss percentage from it is a novel and interesting method. We construct the recovery plan intending to preserve the capelin stock as a prey for the cod, but other benefits such as development for the processing companies and environmental significance for other related species are also concomitant. Thus, the value loss we acquire here can be considered as a reference for the upper bound of the existence value of capelin as a food source for cod.

4. The Refined Heuristic (RH)

4.1 Recovery plan of RH

Proceeding from the Simple Heuristic, we continue to refine the area of the alternative policy in pursuit of more promising capelin recovery and less value loss. From the previous results, we notice that certain states already have little risk of capelin extinction under the optimal policy and appears to have limited improvement when we switch to the alternative policy. Hence, we could alleviate the value loss by avoiding to carry out a non-optimal policy on the area that holds insubstantial need to rebuild capelin.

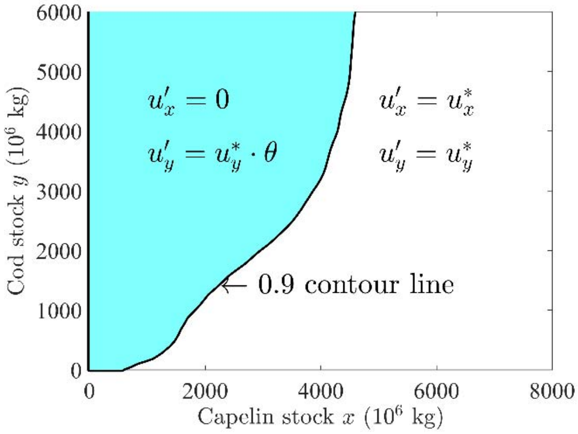

Fig 7. State space area A^{RH} (blue coloured) and corresponding policy of the

Refined Heuristic (RH) recovery plan for capelin and cod

As a result, for the recovery plan of the Refined Heuristic (RH), we establish A^{RH} using the 0.9 contour line of capelin recovery probability under the optimal policy. As displayed in Fig. 7, the blue area A^{RH} includes the states that have a capelin recovery probability less than 90%. It is an attempt to distribute the efforts in a smarter way that they can be put to better use.

4.2. Evaluation of RH

As illustrated in Fig. 8, the capelin recovery rate (figures a,b) and the increased probability of capelin recovery (figures c,d) resemble very much the counterparts from SH under the same value of θ. Shrinking the unnecessary policy deviation does not contribute to notable capelin recovery enhancement but mainly to sparing the value loss.

Evidently, the contour lines of the same values distribute densely and narrowly under RH instead of widely and dispersedly with SH. This has disparate implications depending on where the state stands on the stock space. For the state of $2000 \cdot 10^6$kg capelin and $5000 \cdot 10^6$kg cod, the percentage of value loss is bound to reach the worst case of around 1.3% with $\theta = 1.2$ whichever recovery plan there is. For the state of $4000 \cdot 10^6$kg capelin and $2000 \cdot 10^6$kg cod with $\theta = 1.5$, the percentage of value loss is merely 0.2% for RH but is 1.2% for SH. The recovery plan of RH may not deliver a pronounced improvement regarding value loss in the former case but certainly performs better in the latter case. In addition, the maximum percentage of value loss is lower under RH for either choice of θ and the number of states involved in any definite value losses are much smaller under RH.

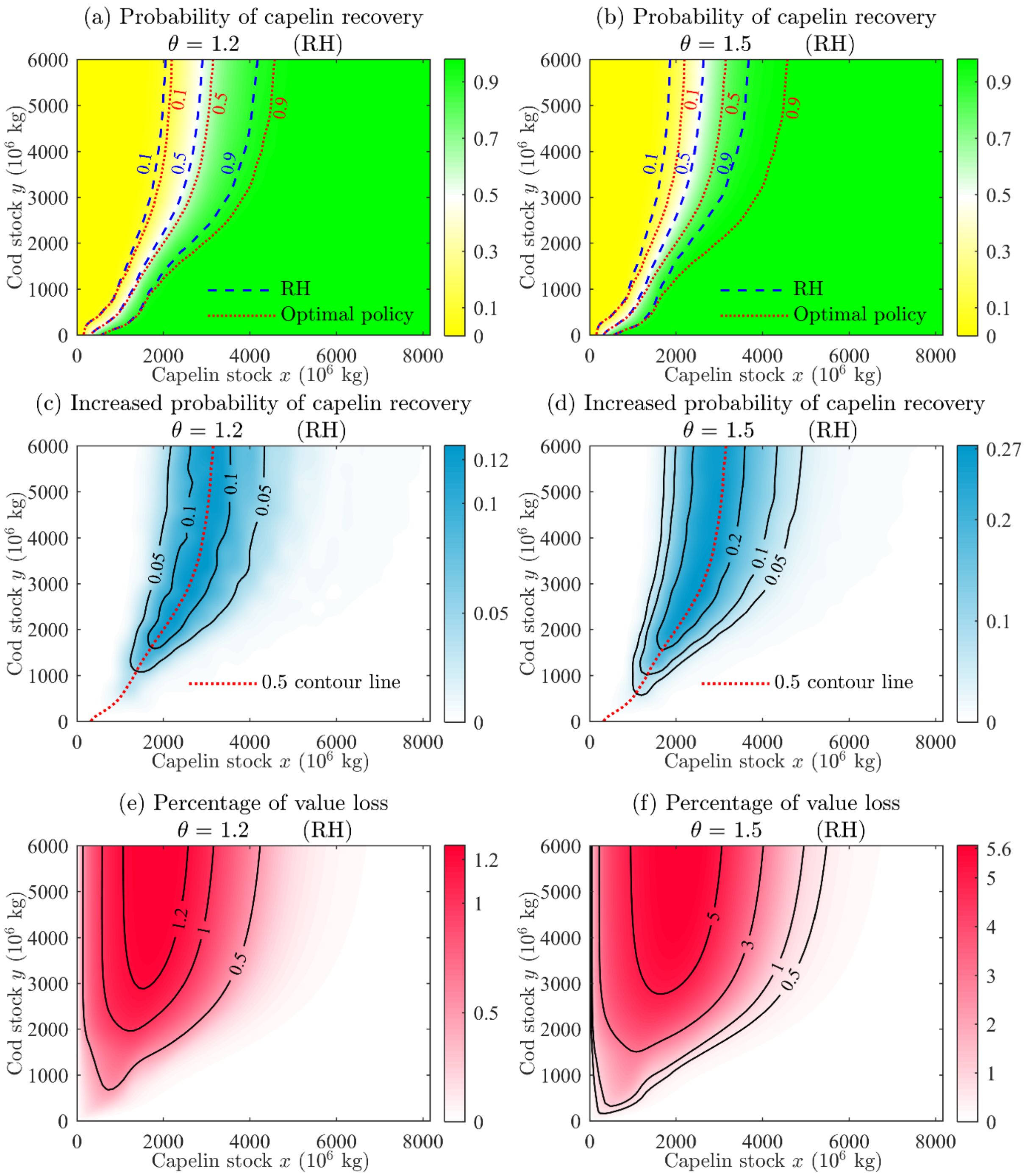

Fig 8. Recovery plan of Refined Heuristic (RH) with $\theta = 1.2$ and $\theta = 1.5$: (a,b) Probability of capelin recovery; (c,d) Increased probability of capelin recovery; (e,f) Percentage of value loss compared with the optimal value

Inspired by the concept of price elasticity of demand in economics, we divide the change of capelin recovery probability by the percentage of value loss and refer to the quotient as the 'value elasticity of recovery'. For various states, the value elasticity of recovery can be very distinct. The following Table 1 lists a comparison of the elasticity for the exact same state under SH and RH. This state lies within the alternative policy region in both recovery plans.

Table 1. Value elasticity of recovery for the state of 2500·10^6kg capelin and 3000·10^6kg cod under recovery plans of SH and RH

Recovery plan	Increased capelin recovery probability	Percentage of value loss	Value elasticity of recovery
SH ($\theta = 1.2$)	12.87%	1.25%	10.3
SH ($\theta = 1.5$)	28.79%	5.56%	5.2
RH ($\theta = 1.2$)	12.30%	0.99%	12.4
RH ($\theta = 1.5$)	27.76%	4.58%	6.1

While the price elasticity of demand in economics measures the responsiveness of the demanded quantity to a change in the price, the value elasticity of recovery estimates the sensitivity of capelin recovery probability increase to a unit of value loss. Under the recovery plan of SH with $\theta = 1.2$, for each percentage of value loss, the alternative policy is able to achieve an average of 10.3% capelin recovery rate increase for the chosen state. As θ rises, the value loss escalates at a higher speed making the value elasticity of recovery generally lower for both SH and RH.

The value elasticity of recovery goes up by roughly 20% from SH to RH under the same θ. This finding reinforces the argument behind RH that the recovery plan is deliberately refined to be more efficient at promoting capelin stock at the same amount of value cost. However, there are apparently some states with a low capelin stock that suffer from value losses but do not enjoy much privilege of capelin recovery. The value elasticity of recovery is zero for such states. Does it imply that it is useless to implement any recovery plan on such an area? We continue to another heuristic that utilizes the innate information from the optimal policy and avoids large area of zero elasticity when capelin stock is poor.

5. The Target Heuristic (TH)

5.1 Recovery plan of TH

After exploring the recovery potentials and value costs under the recovery plans of SH and RH, we pursue to target the relevant stock space area with higher levels of precision and sophistication. In the recovery plan of TH, the variable becomes the area of the alternative policy instead of the value of θ.

The inspiration and justification that lead to constructing A^{TH} are threefold. First, the novel phenomenon of 'super-harvest' remains a major drive behind restricting the alternative policy within the super-harvest boundary. It follows the innate feature from the first-best policy. Second, RH has proven to be more efficient and beneficial in comparison with SH, therefore we continue to utilize the contour lines of capelin recovery probability from the optimal policy. Third, we can observe clearly from Fig. 6(c,d) and 8(c,d) that the increased capelin recovery rates concentrate on a part of the stock space with a capelin stock roughly above $1500 \cdot 10^6$kg. The question follows spontaneously: is it still rewarding to deviate from the optimal policy at a cost of value loss when capelin is weak? It is intriguing to create cases where we switch back to the first-best policy for small capelin stocks.

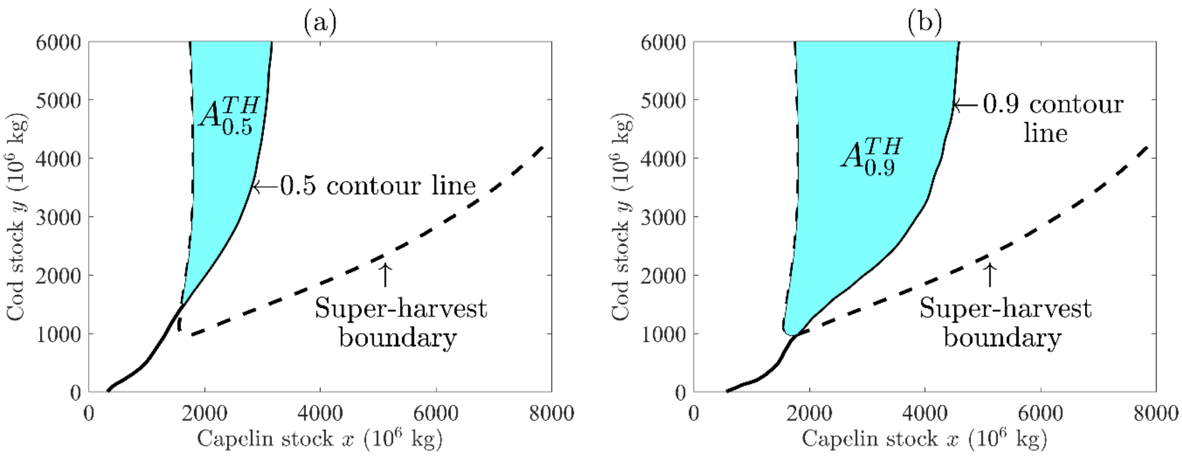

Fig 9. State space areas of the Target Heuristic (TH) recovery plan
for capelin and cod (a) $A_{0.5}^{TH}$ and (b) $A_{0.9}^{TH}$

As displayed in Fig. 9, the narrow blue regions on the stock space lie in between the super-harvest boundary (dashed line) and the 0.5 or 0.9 contour line (solid line). The region of $A_{0.5}^{TH}$ covers the super-harvest area that lend itself to a capelin recovery probability of less than 50%. The area of $A_{0.9}^{TH}$ includes super-harvest states that have a capelin recovery rate of less than 90%. The latter is a stronger tool to preserve capelin and to boost the resilience of the predator-prey system. The recovery plan of TH takes advantage of the information extracted from the optimal policy in order to target very specific states on the stock space. With fewer states being affected by the recovery plan, we escalate the value of θ to 1.8 to produce an intense recovery policy on a concentrated region on the stock space, which also leads to comparable results to the previous SH and RH.

5.2. Evaluation of TH

We discover that the case of $A_{0.5}^{TH}$ with $\theta = 1.8$ produces similar results as SH and RH with $\theta = 1.2$ and the case of $A_{0.9}^{TH}$ with $\theta = 1.8$ generates resembling results to SH and RH with $\theta = 1.5$. For SH and RH, a large part of the state space is involved in some level of recovery rate increase but for many states it is merely neglectable. However, for TH the states with enhancements are more gathered within a outlined area. If we reckon the outermost contour line as a threshold for any noteworthy improvement, then the areas inside the 0.05 contour lines in Fig. 10(c,d) are marginally smaller than their counterparts in SH and RH. In addition, the maximum of capelin recovery rate increase is the highest under TH. The recovery plan of TH successfully achieves rather adequate capelin recovery effects and comparable results to those from SH and RH.

Compared to SH and RH, the recovery plan of TH employs a higher θ on a smaller targeted area, which is a trade-off between the number of states that lend themselves to alternative policies and the degree of deviation from the optimal policy. From Fig. 10(a), we notice that the 0.5 contour line shifts towards left to the utmost extent among the three contour lines, which is not the case for SH and RH. This is also reflected in Fig. 10(c) that the dark blue area mainly gathers to the left of 0.5 contour line. Moreover, the spaces between the 0.05 and 0.1 contour line are much tighter than that of SH and RH, indicating a sharper rise of improvement with $A_{0.5}^{TH}$. For the case of $A_{0.9}^{TH}$, the main differences emerge around the lower left corner of the state space. This region is left out by the super-harvest and is therefore not targeted under TH. As a result, the dark blue area in Fig. 10(d) distributes alongside the red dotted 0.5 contour line and ends where cod stock is above $1000 \cdot 10^6$kg while for SH and TH, it elongates and spreads until where cod is about $500 \cdot 10^6$kg.

For SH and RH, we seek to rescue inadequate capelin stocks even though they are much likely to develop towards extinction. The recovery plan manages to prolong the process of capelin collapse, which endows the value of capelin existing for a longer period of time in the system. For TH, the implicit argument is that the efforts to sustain the weak capelin states are not worthy and therefore we decide to extract the remaining commercial values from the system. Instead of trying to keep the poor capelin stocks, doomed sooner or later, present for more years, we focus on altering the ending for capelin on the selected parts of the state space, i.e. $A_{0.5}^{TH}$ and $A_{0.9}^{TH}$. Such distinctions consequently spawn considerable differences with regards to the percentage of value loss.

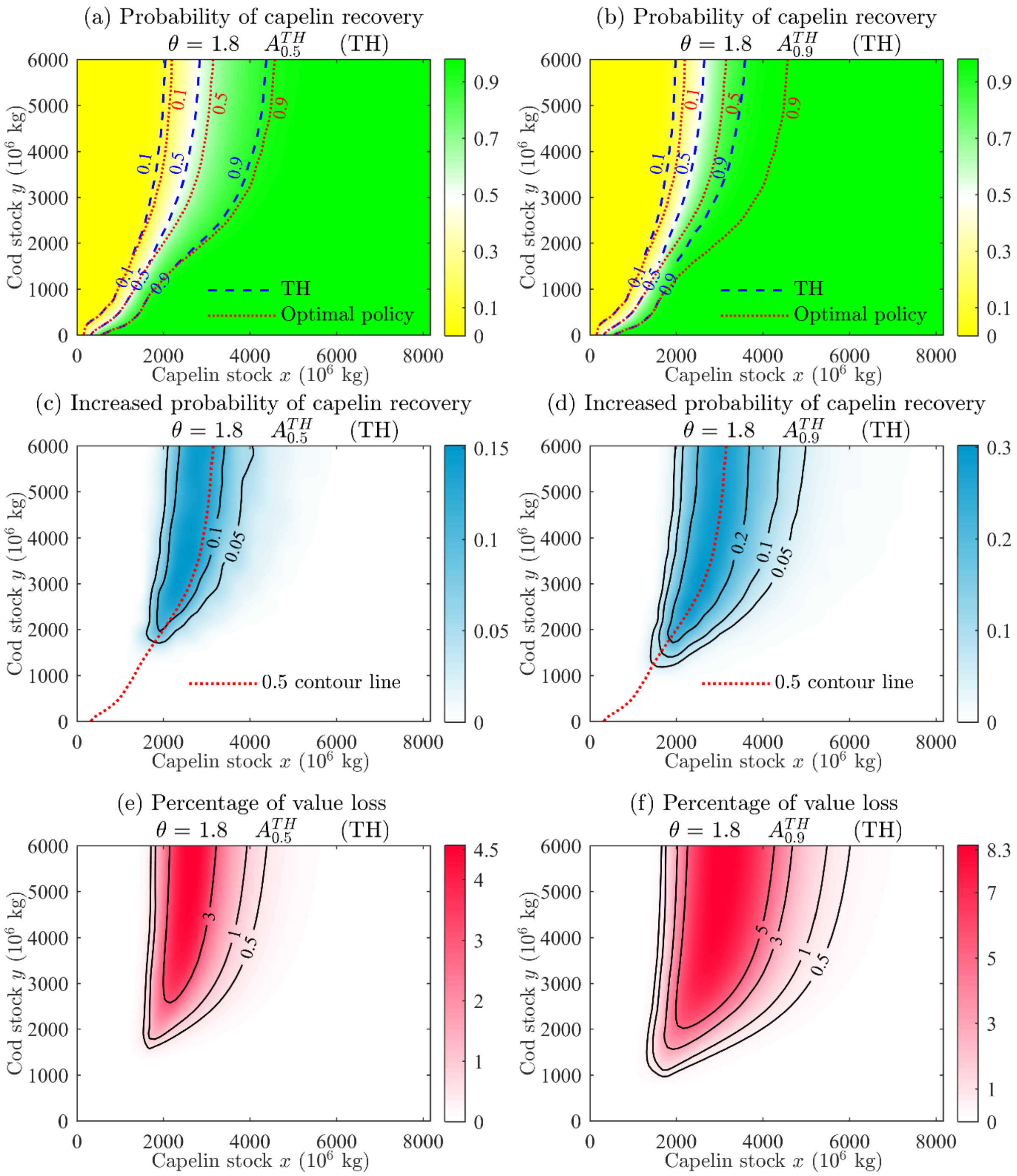

Fig 10. Recovery plan of Target Heuristic (TH) with $A_{0.5}^{TH}$ and $A_{0.9}^{TH}$:
(a,b) Probability of capelin recovery; (c,d) Increased probability of capelin recovery;
(e,f) Percentage of value loss compared with the optimal value

For most of the states with a capelin stock less than 2000·10^6kg, implementing the recovery plan of TH leads to zero value loss. But a weak capelin stock could experience a percentage of value loss up to 5% using SH and RH. If we put the case of $A_{0.5}^{TH}$ in Fig. 10(e) together with the case of SH when $\theta = 1.2$ in Fig. 8(e), we see that the worst of value loss is 4.5% for the former and 1.2% for the later. The 0.5 contour lines signify an extensive shrinkage of the dark red area. For the majority of states, the value under the recovery plan of $A_{0.5}^{TH}$ does not deviate from the optimal value function. But for the ones that do deviate, bigger sacrifices in value are made in order to acknowledge the ecological importance of the prey. Similar characteristics hold for the case of $A_{0.9}^{TH}$ in Fig. 10(f) and the case of SH when $\theta = 1.5$ in Fig. 8(f). The highest percentage of value loss is 8.3% for the former and 6% for the latter, with a smaller gap between the two. Again, the outermost 0.5 contour lines manifest an obvious reduction of the 'suffering' area. And the innermost 5 contour lines reveal that the percentage of value loss rockets drastically towards the centre under TH.

The value elasticity of recovery for the same state ($2500 \cdot 10^6$kg capelin and $3000 \cdot 10^6$kg cod) is 4.36 for the case of $A_{0.5}^{TH}$ and 4.03 for the case of $A_{0.9}^{TH}$. Since the value of θ remains unchanged, it is expected that the two elasticities are close. Similar to previous results, the case of a stronger deviation from the optimal policy yields a lower value elasticity of recovery. It is also anticipated that the elasticity numbers from SH and RH are higher than those from TH. The distinctive design about TH is to let a smaller number of states carry the gains and losses of a more intensive approach. For this specified state, one percentage of value loss exchanges approximately four percentage of increase of capelin recovery probability. To determine whether this number can be considered sufficient would be another potential research direction.

6. Conclusion and discussion

In our stochastic predator-prey setting, a capelin stock develops towards two opposite endings: a prosperous ecosystem or a devasted one. We discover that the optimal policy inherently makes an effort to promote the prey, sometimes going so far as to be even greedier than the 'greedy harvest' for the predator. The super-harvest is an unconventional and thought-provoking discovery. A certain amount of economic benefit is sacrificed through excessive predator removal in order to drive the states faster into the region of capelin growth so that the risk of prey collapse becomes lessened. Note that the optimization objective does not put extra value on having an ecosystem instead of a single stock. Therefore, the super-harvest phenomenon implies that even though no existence value of the prey is deliberately counted, the optimal solution somehow calls out for maintaining the food source in the system for a longer period of time. The value loss could be reckoned as a reference for the upper bound of the existence value of the prey.

It has been shown that implementation of adequate policies to reduce fishing mortality is crucial for overexploited stocks to recover, underlining the positive impacts of science-based management (Zimmermann & Werner, 2019). The idea of acting greedily at harvesting the predator in order to spare the prey guides our heuristics that seek to rebuild the prey stock. To elevate the resilience of the system, we need to alter the probability of capelin extinction and recovery intentionally by deviating from the first-best policy.

One could potentially produce alternative management plans that are instantly effective but come with an unacceptable cost. Thus, we propose a succession of heuristics that modify the optimal policy in a way that both promote capelin recovery and limit the value loss. We generate three recovery plans with various degrees of complexity. The Simple Heuristic (SH) follows a straightforward rule that all states with a capelin stock less than a certain level apply the alternative policy. The Refined Heuristic (RH) selects the states with a capelin recovery rate less than 90%. The Target Heuristic (TH) focuses on the states of super-harvest that at the same time has a recovery rate less than 50% or 90%. Within the active area of the recovery plan, capelin harvest is zero and cod harvest is scaled up with parameter θ.

Our results show that all of the recovery plans manage to lift capelin recovery probabilities and shift the contour lines. The improvement in recovery rate mainly takes place around the contour line of 50% under the optimal policy. It is not a surprise that the approach contributes most to the area of states where future development is most obscure. The similarities dominate the results between SH and RH. When $\theta = 1.2$, the capelin recovery probability can grow by as much as around 13%. When $\theta = 1.5$, the maximum capelin recovery rate increase is roughly 28%.

While RH performs slightly better than SH regarding recovery, it delivers a much more visible difference regarding value loss percentage. The refined plan under RH successfully avoids unnecessary value losses on numerous states. With a specific example state, we demonstrate that this leads to at least 20% increase in value elasticity of recovery for RH. The value elasticity of recovery reflects the efficiency of transferring one percent of value loss into recovery probability growth and the exquisiteness in the design of the policy. The choice of θ is certainly crucial for the elasticity and should depend on the urgency degree of rebuilding the endangered stock.

The TH selects part of the super-harvest area and sets the cod harvest to 1.8 times of the first-best policy. It resembles a sharp knife with intense effort on a tiny state space area, creating comparable recovery results and concentrated value losses. Very poor capelin stocks are directly harvested in the same resolute way as the optimal policy. The maximum value loss is 4.5% while this number is only about 1.3% for SH and RH under $\theta = 1.2$. The worst value loss is 8.3% while it is around 5.8 % for SH and RH under $\theta = 1.5$.

Let us assume the first 'jump' is from zero capelin recovery probability increase to the mild cases with a maximum increment below 15% and the second 'jump' is from the mild to the best improvements. An intriguing question is: what is smarter to do? To make the first jump, SH and RH lend themselves to a minor loss in value while TH chooses to sacrifice a small group of states. It is a judgement call to determine which strategy is more suitable depending on specific constraints. To make the second jump, both the area and level of value loss roughly double under TH. But for SH and RH, in addition to the area expansion the level of value loss has rocketed much more. It seems smarter to work with the area refinement than to simply increase θ when we seek to move from modest to pronounced recovery improvement. We emphasize the importance of the super-harvest finding and hope for better processes to target the accurate state space area for stock recovery with future research.

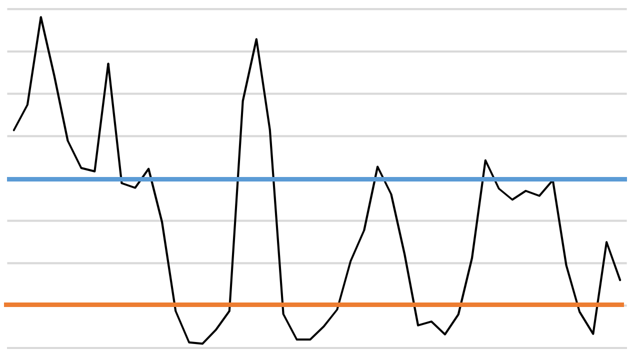

Fig 11. Total biomass of capelin stock in the Barents Sea from 1973 to 2017 with unit of 10^6 kg

The capelin stock in the Barents Sea has a history of repeated collapses during the recent 50 years (Gjøsæter, Bogstad, & Tjelmeland, 2009). As displayed in Fig. 11, we highlight the most relevant range of states between $1000 \cdot 10^6$kg and $4000 \cdot 10^6$kg using colored solid lines. Yearly state transitions take place in a drastic and sharp manner inside this range. The overall trend is decreasing over the years despite the volatile ups and downs. Better stock management is called for in order to maintain a healthy ecosystem.

For the three times where capelin stock hit bottom and bounced above the blue line of $4000 \cdot 10^6$kg afterwards, it took 4-5 years to rise above the yellow line of $1000 \cdot 10^6$kg. According to our study, even with increased predator removal and banned capelin harvest, not much can be improved when capelin is extremely weak. A period of 5 consecutive years with a collapsed capelin stock signifies huge economic losses. Precautionary measures should be taken to avoid capelin state dropping below the lower yellow line. With the recovery plans proposed in our paper, we establish a buffer area on the state space with enhanced growth for capelin. It helps not only to rebuild the stock faster but more importantly to escape being trapped in a poor state for years.

Appendix

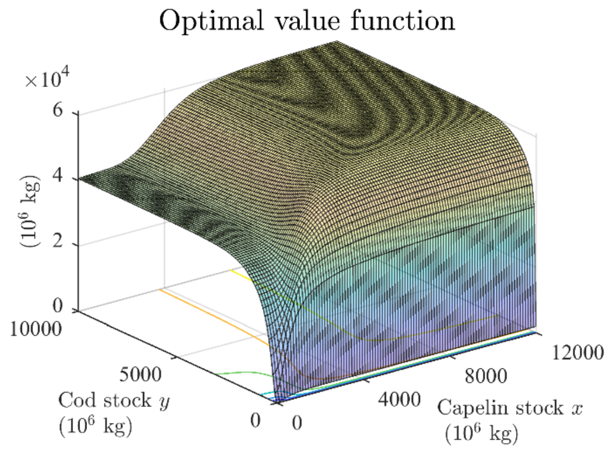

Fig A. Optimal value function

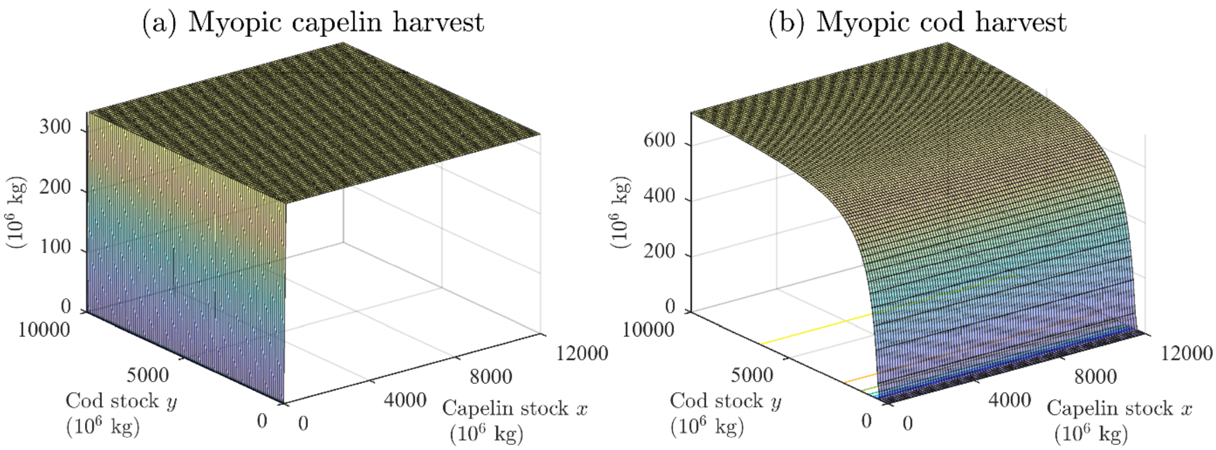

Fig B. Myopic harvest policy for (a) capelin and (b) cod

References

Agnarsson, S., Arnason, R., Johannsdottir, K., Ravn-Jonsen, L., Sandal, L. K., Steinshamn, S. I., & Vestergaard, N. (2008). *Comparative evaluation of the fisheries policies in Denmark, Iceland and Norway: Multispecies and stochastic issues*. Retrieved from https://brage.bibsys.no/xmlui/handle/11250/165057

Bogstad, B., Hauge, K., & Ulltang, Ø. (1997). MULTSPEC - A Multi-species Model for Fish and Marine Mammals in the Barents Sea. *Journal of Northwest Atlantic Fishery Science*, *22*, 317–341.

Britten, G. L., Dowd, M., Kanary, L., & Worm, B. (2017). Extended fisheries recovery timelines in a changing environment. *Nature Communications*, *8*, 15325. https://doi.org/10.1038/ncomms15325

Bruce, M., J, P. A., & Christopher, C. (2009). Optimally Managing a Stochastic Renewable Resource under General Economic Conditions. *The B.E. Journal of Economic Analysis & Policy*, *9*(1), 1–31.

Charles, A. T. (1998). Living with uncertainty in fisheries: Analytical methods, management priorities and the Canadian groundfishery experience. *Fisheries Research*, *37*(1), 37–50. https://doi.org/10.1016/S0165-7836(98)00125-8

Charles, A. T., & Munro, G. R. (1985). Irreversible Investment and Optimal Fisheries Management: A Stochastic Analysis. *Marine Resource Economics*, *1*(3), 247–264. https://doi.org/10.1086/mre.1.3.42628859

Clark, C. W. (1990). *Mathematical Bioeconomics: The Optimal Management of Renewable Resources, 2nd Edition* (2 edition). New York: Wiley-Interscience.

Clark, C. W. (2010). *Mathematical Bioeconomics: The Mathematics of Conservation* (3 edition). Hoboken, N.J: Wiley.

Clark, C. W., & Kirkwood, G. P. (1986). On uncertain renewable resource stocks: Optimal harvest policies and the value of stock surveys. *Journal of Environmental Economics and Management*, *13*(3), 235–244. https://doi.org/10.1016/0095-0696(86)90024-0

Dalpadado, P., & Bogstad, B. (2004). Diet of juvenile cod (age 0–2) in the Barents Sea in relation to food availability and cod growth. *Polar Biology*, *27*(3), 140–154. https://doi.org/10.1007/s00300-003-0561-5

FAO. (2008). The State of World Fisheries and Aquaculture—FAO Fisheries and Aquaculture Dept, Food and Agriculture Organization of the United Nations. (SOFIA). Retrieved June 13, 2018, from http://www.fao.org/docrep/011/i0250e/i0250e00.htm

Flaaten, O., Salvanes, A., Schweder, T., & Ulltang, Ø. (1998). Objectives and uncertainties in fisheries management with emphasis on three North Atlantic Ecosystems. *Fisheries Research*, (37), 1–337.

Fleming, C. M., & Alexander, R. R. (2002). *Single Species Versus Multiple Species Models: The Economic Implications* (No. 23693). Retrieved from Massey University, Centre for Applied Economics and Policy Studies website: https://ideas.repec.org/p/ags/masdpn/23693.html

Gjøsæter, H., Bogstad, B., & Tjelmeland, S. (2009). Ecosystem effects of the three capelin stock collapses in the Barents Sea. *Marine Biology Research*, *5*(1), 40–53. https://doi.org/10.1080/17451000802454866

Hannesson, R. (1987). Optimal catch capacity and fishing effort in deterministic and stochastic fishery models. *Fisheries Research*, *5*(1), 1–21. https://doi.org/10.1016/0165-7836(87)90012-9

Hjermann, D. Ø., Bogstad, B., Eikeset, A. M., Ottersen, G., Gjøsæter, H., & Stenseth, N. C. (2007). Food web dynamics affect Northeast Arctic cod recruitment. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1610), 661–669. https://doi.org/10.1098/rspb.2006.0069

Hollowed, A. B., Bax, N., Beamish, R., Collie, J., Fogarty, M., Livingston, P., … Rice, J. C. (2000). Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? *ICES Journal of Marine Science*, *57*(3), 707–719. https://doi.org/10.1006/jmsc.2000.0734

Howarth, R. B. (1995). Sustainability under Uncertainty: A Deontological Approach. *Land Economics*, *71*(4), 417–427. https://doi.org/10.2307/3146707

Judd, K. L. (1998). *Numerical Methods in Economics*. Cambridge, Mass: The MIT Press.

Kama, A. A. L., & Schubert, K. (2004). Growth, Environment and Uncertain Future Preferences. *Environmental and Resource Economics*, *28*(1), 31–53. https://doi.org/10.1023/B:EARE.0000023820.15522.a4

Kar, T. K., & Chaudhuri, K. S. (2004). Harvesting in a two-prey one-predator fishery: A bioeconomic model. *The ANZIAM Journal*, *45*(3), 443–456. https://doi.org/10.1017/S144618110001347X

Kasperski, S. (2010). *Optimal Multispecies Harvesting in the Presence of a Nuisance Species* (2010 Annual Meeting, July 25-27, 2010, Denver, Colorado No. 61718). Retrieved from Agricultural and Applied Economics Association website: https://econpapers.repec.org/paper/agsaaea10/61718.htm

Kugarajh, K., Sandal, L. K., & Berge, G. (2006). Implementing a Stochastic Bioeconomic Model for the North-East Arctic Cod Fishery. *Journal of Bioeconomics*, *8*(1), 35–53. https://doi.org/10.1007/s10818-005-5783-x

Kvamsdal, S. F., Poudel, D., & Sandal, L. K. (2016). Harvesting in a Fishery with Stochastic Growth and a Mean-Reverting Price. *Environmental and Resource Economics*, *63*(3), 643–663. https://doi.org/10.1007/s10640-014-9857-x

Link, J. S., Ihde, T. F., Harvey, C. J., Gaichas, S. K., Field, J. C., Brodziak, J. K. T., … Peterman, R. M. (2012). Dealing with uncertainty in ecosystem models: The paradox of use for living marine resource management. *Progress in Oceanography*, *102*, 102–114. https://doi.org/10.1016/j.pocean.2012.03.008

Maravelias, C. D., Damalas, D., Ulrich, C., Katsanevakis, S., & Hoff, A. (2011). Multispecies fisheries management in the Mediterranean Sea: Application of the Fcube methodology. *Fisheries Management and Ecology*, *19*(3), 189–199. https://doi.org/10.1111/j.1365-2400.2011.00801.x

May, R. M., Beddington, J. R., Clark, C. W., Holt, S. J., & Laws, R. M. (1979). Management of multispecies fisheries. *Science (New York, N.Y.)*, *205*(4403), 267–277. https://doi.org/10.1126/science.205.4403.267

Nøstbakken, L., & Conrad, J. M. (2007). Uncertainty in Bioeconomic Modelling. In *International Series In Operations Research Amp; Mana. Handbook Of Operations Research In Natural Resources* (pp. 217–235). https://doi.org/10.1007/978-0-387-71815-6_12

Posch, O., & Trimborn, T. (2010). *Numerical solution of continuous-time DSGE models under Poisson uncertainty* (No. dp-450). Retrieved from Leibniz Universität Hannover, Wirtschaftswissenschaftliche Fakultät website: https://ideas.repec.org/p/han/dpaper/dp-450.html

Poudel, D., Sandal, L. K., Steinshamn, S. I., & Kvamsdal, S. F. (2012). Do Species Interactions and Stochasticity Matter to Optimal Management of Multispecies Fisheries? In G. H. Kruse, H. I. Browman, K. L. Cochrane, D. Evans, G. S. Jamieson, P. A. Livingston, & D. Woodby, *Global Progress in Ecosystem-Based Fisheries Management* (pp. 209–236). https://doi.org/10.4027/gpebfm.2012.011

Poudel, Diwakar, Sandal, L. K., & Kvamsdal, S. F. (2015). Stochastically Induced Critical Depensation and Risk of Stock Collapse. *Marine Resource Economics*, *30*(3), 297–313. https://doi.org/10.1086/680446

Poudel, Diwakar, Sandal, L. K., Steinshamn, S. I., & Kvamsdal, S. F. (2014). *Long-term sustainable and optimal management of multispecies stochastic fisheries* [Working paper]. Retrieved from SNF website: https://brage.bibsys.no/xmlui/handle/11250/193114

Rosa, R., Vaz, J., Mota, R., & Silva, A. (2018). Preference for Landings' Smoothing and Risk of Collapse in Optimal Fishery Policies: The Ibero-Atlantic Sardine Fishery. *Environmental and Resource Economics*, *71*(4), 875–895. https://doi.org/10.1007/s10640-017-0187-7

Roughgarden, J., & Smith, F. (1996). Why fisheries collapse and what to do about it. *Proceedings of the National Academy of Sciences*, *93*(10), 5078–5083. https://doi.org/10.1073/pnas.93.10.5078

Sanchirico, J. N., & Springborn, M. (2011). How to Get There From Here: Ecological and Economic Dynamics of Ecosystem Service Provision. *Environmental and Resource Economics*, *48*(2), 243–267. https://doi.org/10.1007/s10640-010-9410-5

Sandal, L. K., & Steinshamn, S. I. (2010). Rescuing the Prey by Harvesting the Predator: Is It Possible? In *Energy Systems*. *Energy, Natural Resources and Environmental Economics* (pp. 359–378). https://doi.org/10.1007/978-3-642-12067-1_20

Sandal, L. K., & Steinshamn, S. I. (2017). A Stochastic Feedback Model for Optimal Management of Renewable Resources. *Natural Resource Modeling*, *10*(1), 31–52. https://doi.org/10.1111/j.1939-7445.1997.tb00209.x

Sethi, G., Costello, C., Fisher, A., Hanemann, M., & Karp, L. (2005). Fishery management under multiple uncertainty. *Journal of Environmental Economics and Management*, *50*(2), 300–318. https://doi.org/10.1016/j.jeem.2004.11.005

Singh, R., Weninger, Q., & Doyle, M. (2006). Fisheries management with stock growth uncertainty and costly capital adjustment. *Journal of Environmental Economics and Management*, *52*(2), 582–599. https://doi.org/10.1016/j.jeem.2006.02.006

Teh, L. S., Cheung, W. W., Christensen, V., & Sumaila, U. (2017). Can we meet the Target? Status and future trends for fisheries sustainability. *Current Opinion in Environmental Sustainability*, *29*, 118–130. https://doi.org/10.1016/j.cosust.2018.02.006

Woodward, R. T., & Bishop, R. C. (1999). Optimal-Sustainable Management of Multi-Species Fisheries: Lessons from a Predator-Prey Model. *Natural Resource Modeling*, *12*(3), 355–377. https://doi.org/10.1111/j.1939-7445.1999.tb00017.x

Yodzis, P. (1994). Predator-Prey Theory and Management of Multispecies Fisheries. *Ecological Applications*, *4*(1), 51–58. https://doi.org/10.2307/1942114

Zimmermann, F., & Werner, K. M. (2019). Improved management is the main driver behind recovery of Northeast Atlantic fish stocks. *Frontiers in Ecology and the Environment*, *17*(2), 93–99. https://doi.org/10.1002/fee.2002

NHH

NORGES HANDELSHØYSKOLE
Norwegian School of Economics

Helleveien 30
NO-5045 Bergen
Norway

T +47 55 95 90 00
E nhh.postmottak@nhh.no
W www.nhh.no