Optimal Harvest in a Multi-species Age Structured Fishery

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Content

- Background and Motivation
- Model
- Data and Parameter Estimation
- Preliminary Findings
- Conclusions

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- Data and Parameter Estimation
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- Data and Parameter Estimation
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Background and Motivation

- While surplus bioeconomic models are very common among fisheries economists, age structured modelling has gaining more and more popularity because of the possibility to do optimization (Steinshamn, 2011 Tahvonen et al. (2013))
- Fisheries managers and including some authors think that age structured population models are more realistic models and the biomass approach may only serve as a pedagogical tool (Wilen 2000)

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Background and Motivation

- Unlike lumped parameters in the surplus growth model, in age-structured models, there are individual parameters (or functions) for all biological phenomena.
- A large variety of bioeconomic age-structured models have now been developed (for example see Tahvonen 2011) .
- Given the importance of ASM, we plan to develop a multispecies ASM to suggest optimal harvest policies for Barents sea cod and capelin species.

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Literatures

This paper is based on some specific literatures.

- Steinshamn (2011) which is theoretical paper and highlights that stock density dependency plays greater role in the optimal management of fishery.
- Tahvonen et al. (2013) discuss optimal harvesting strategy in a single species age structured model. They have also analyzed the effect of predators on the optimal policy of the prey species (but not multispecies context).

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Objective of the Paper

The objective is to develop multispecies age structured optimization model that include density dependency. Basically, this is an application of theoretical model by Steinshamn (2011). We compare optimal harvest policies in age structured population for both single species and multispecies context.

Model

Let x and y are the stock species (capelin and cod) , $t = 1 : T$ is the time period, $a = 1 : A$ is the age of the species x and y.

The objective is to maximize discounted revenue over the given time horizon:

$$
\begin{aligned}
Max\pi &= \beta^t \{ \sum_{t=1}^{T} \sum_{a=1}^{A} (P_x w_{x,a} C_{x,a,t}) \\
&+ \sum_{t=1}^{T} \sum_{a=1}^{A} ((P_y w_{x,a} C_{y,a,t})) - \sum_{t=1}^{T} (K_x E_{x,t} + K_y E_{y,t}) \}
\end{aligned} \tag{1}
$$

subjected to **Stock Dynamics, Effort Restriction and Sustainability Constraints**.

Where, π is discounted profit, p_x is the price of capelin, P_y is the price of cod species, $w_{x,a}$ is weight of capelin, $w_{y,a}$ is weight of cod, $C_{x,a,t}$ is the catch of capelin, $C_{y,a,t}$ is catch of cod, $E_{x,t}$ capelin catch effort, and $E_{y,t}$ Cod catch effort, K_x is cost of capelin catch effort, K_y is cost of cod catch effort. $\beta = 1/(1 + r)$ is the discount factor.

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Model

The stock dynamics x and y can be given as:

$$N_{x,a+1,t+1} = [(N_{x,a,t}^{1-\alpha} + \frac{k_x h_x E_{x,t}}{M_{x,a}}) \exp(-M_x(1-\alpha)t) - \frac{k_x h_x E_{x,t}}{M_{x,a}}]^{\frac{1}{(1-\alpha)}} \tag{2}$$

$$N_{y,a+1,t+1} = [(N_{y,a,t}^{1-\alpha} + \frac{k_y h_y E_{y,t}}{M_{y,a}}) \exp(-M_y(1-\alpha)t) - \frac{k_y h_y E_{y,t}}{M_{y,a}}]^{\frac{1}{(1-\alpha)}} \tag{3}$$

where , $N_{x,a,t}$ and $N_{y,a,t}$ is the number of individual of capelin and cod. h_x,, h_y, k_x are k_y are age specific parameter. $M_{x,a}$ and $M_{y,a}$ are age specific mortality rates.
$k_x h_x E_{x,t}$ and $k_y h_y E_{y,t}$ are fishing mortality of species x, y.

Here α is schooling parameter or density parameter. In the special case, when $\alpha = 1$, by taking the limit, these equations (2 and 3) reduce to Beverton Holt expression.

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Model

and the restriction on Effort is given as:

$$E^{max}_{x,t} = \frac{N^{1-\alpha}_{x,a,t} M_{x,a}}{k_x h_x [\exp(M_{x,a}(1-\alpha))]} \quad (4)$$

$$E^{max}_{y,t} = \frac{N^{1-\alpha}_{y,a,t} M_{y,a}}{k_y h_y [\exp(M_{y,a}(1-\alpha))]} \quad (5)$$

We also assume that at the end of the period T, $N_{x,T} \geq \overline{N_x}$ and $N_{y,T} \geq \overline{N_y}$ where, $\overline{N_x}$ and $\overline{N_y}$ are the minimum stock size (**the sustainability constraints**).

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Catch Function

The catch functions for capelin and cod species can be specified as:

$$C_{x,a,t} = \int_{t}^{t+1} k_x h_x E_{x,t} \{ [N_{x,a,t}^{1-\alpha} + \frac{k_x h_x E_{x,t}}{M_{x,a}}] e^{(-M_x(1-\alpha)t)} - \frac{k_x h_x E_{x,t}}{M_{x,a}} \}^{\frac{1}{1-\alpha}} d\tau \quad (6)$$

$$C_{y,a,t} = \int_{t}^{t+1} k_y h_y E_{y,t} \{ [N_{y,a,t}^{1-\alpha} + \frac{k_y h_y E_{y,t}}{M_{y,a}}] e^{(-M_y(1-\alpha)t)} - \frac{k_y h_y E_{y,t}}{M_{y,a}} \}^{\frac{1}{1-\alpha}} d\tau \quad (7)$$

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Total Biomass

The total biomass of capelin ($B_{x,t}$)and cod ($B_{y,t}$) at time t is given by:

$$B_{x,t} = \sum_{a}^{A}(N_{x,a,t}w_{x,a}); \qquad B_{y,t} = \sum_{a}^{A}(N_{y,a,t}w_{y,a}) \tag{8}$$

and the spawning stock biomass for capelin ($SSB_{x,t}$) and cod stocks ($SSB_{y,t}$) is given as:

$$SSB_{x,t} = \sum_{a}^{A}(N_{x,a,t}sw_{x,a}m_{x,a}) \qquad SSB_{y,t} = \sum_{a}^{A}(N_{y,a,t}sw_{y,a}m_{y,a}) \tag{9}$$

Where, sw_x and sw_y are weight of spawning stock of capelin and cod and $m_{x,a}$ and $m_{y,a}$ are age specific maturity index.

Recruitment Function

We choose **Beverton-Holt recruitment function** to estimate the recruitment parameters.

$$R_x = \frac{\psi_{x1} SSB_{x,t}}{(1 + \psi_{x2} SSB_{x,t})} \qquad R_y = \frac{\psi_{y1} SSB_{y,t}}{(1 + \psi_{y2} SSB_{y,t})} \tag{10}$$

$SSB_{x,t}$ and $SSB_{y,t}$ are spawning stock biomass for capelin and cod stocks. The terms ψ_{x1} ,ψ_{x2} , ψ_{y1} and ψ_{y2} are recruitments parameters.

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Mortality and Weight Gain

The total mortality of capelin is natural mortality and the predation by the cod and is a function of cod biomass.

$$M_{xp} = f(M_x, B_{y,t})) = M_x + g(B_{y,t}) = M_x + (B_{y,t})^b$$

While the weight gain in cod species due to the predation of capelin is a function of the capelin biomass

$$w_{yp} = h(w_y, B_{x,t})) = w_y + j(B_{y,t}) = w_y + (B_{x,t})^b$$

Where M_{xp} is the total mortality, M_x is the natural mortality, w_{yp} is the total weight gain, w_y is the normal weight and b is parameter.

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Parameters and initial values

Table 1: Biological parameters and initial values of capelin species used in optimization

Parameters	Value	Sources /Comments
Initial number of individuals at age class $N_{x,a}$	[321.775e+9 234.137e+9 52.261e+9 4.866e+9]	Based on data in ICES (2013)
Mean stock weight (kg) at age $w_{x,a}$	[0.00318 0.008 0.01554 0.02249]	Based on data in ICES (2013)
Natural mortality $M_{x,a}$	[0.465 0.3 0.2 0.2]	Based on data in ICES (2013)
Maturity index $m_{x,a}$	[0.00074276 0.13758 0.70712 0.93033]	Based on data in ICES (2013)
Mean spawning stock weight (kg) $s_{x,a}$	[0.012766 0.015609 0.018033 0.023327]	Based on data in ICES (2013)
Beverton Holt recruitment parameters ψ_x	[461.51 1.358e-09]	Estimated from the data in ICES (2013)
Age specific selectivity parameter $k_{x,a}$	[0.4 0.6 01 01]	Arbitrarily chosen
Age specific density parameter $h_{x,a}$	[0.81 0.81 0.81 0.81]	Arbitrarily chosen

Parameters and initial values

Table 2: Biological parameters and initial values of cod species used in optimization

Parameters	Value	Sources /Comments
Initial number of individuals at age class $N_{y,a}$	[623861e+3 376388e+3 184745e+3 259604e+3 293770e+3 184821e+3 53976e+3 24816e+3 11048e+3 7560e+3 2220e+3]	Based on data in ICES (2013)
Mean stock weight (kg) at age $w_{y,a}$	[0.21 0.561 1.108 1.76 2.775 4.056 6.117 8.718 11.676 12.731 14.311]	Based on data in ICES (2013)
Natural mortality $M_{y,a}$	[0.4088 0.3548 0.2572 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2]	Based on data in ICES (2013)
Maturity index $m_{y,a}$	[0 0 0.003 0.1 0.196 0.561 0.798 0.993 1 1 1]	Based on data in ICES (2013)
Mean spawning stock weight (kg) $s_{y,a}$	[1.700 2.457 3.4830 4.570 6.183 7.497 9.090 11.124 11.448 12.240 15.030]	Based on data in ICES (2013)
Beverton Holt recruitment parameters ψ_y	[8.7347 1.4175e-08]	Estimated from the data in ICES (2013)

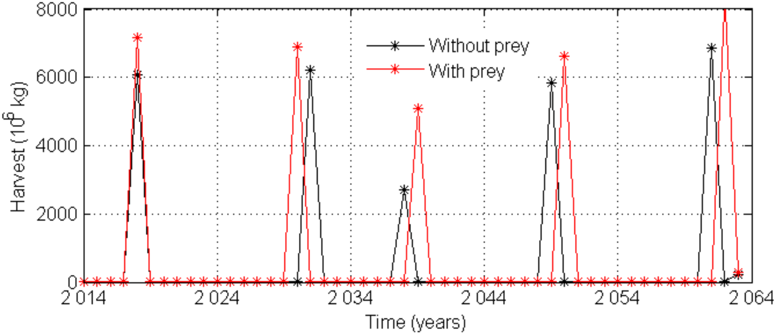
Parameters and initial values

Table 3: Economic parameters for capelin and cod for optimization

Parameters	Value	Sources /Comments
Cost of capelin harvest NOK K_x	0.07	ref
Capelin price NOK per kg P_x	2.36	Fiskeridirektoratet (2011)
Cost of cod harvest NOK K_y	0.2	ref
Cod price NOK per kg P_y	10.56	Fiskeridirektoratet (2011)
Discount rate r	0.02	Arbitrarily chosen
Schooling parameter α	0-1	Arbitrarily chosen

Preliminary Results

Optimal Harvest Policy for Cod Species



Here, we assume α=1 for cod and α=0 for capelin

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Preliminary Results

Pulse Fishing vs Uniform Fishing

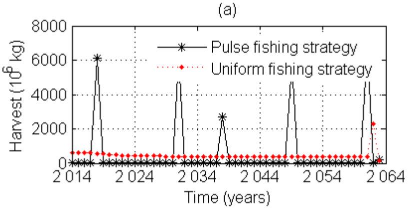
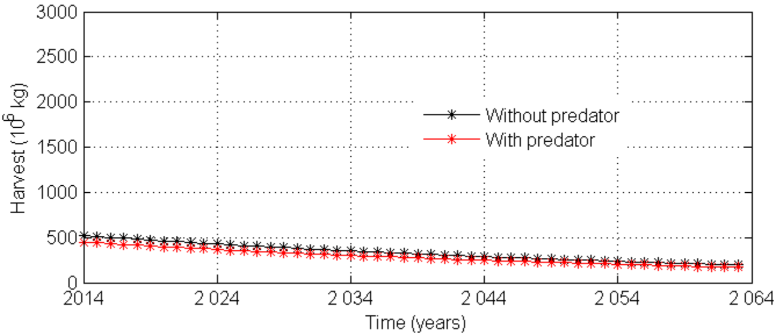


Figure: Different optimal harvest strategy in cod species (a) single species model (b) Multispecies model

Preliminary Results

Optimal Harvest Policy for Capelin Species



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Preliminary Results

Net Present Value: Single species Model vs Multispecies Model

Table: Net present value (NPV) NOK in different Model scenarios at $\delta = 0.02$

Scenarios	Cod Speceis	Capelin Species	Total
Single species model	1.8045e+11	4.7074e+09	1.8516e+11
Multispecies model	2.2003e+11	4.0932e+09	2.2412e+11
Difference	3.9580e+10	614200000	3.8966e+10
Change (%)	21.9	13.0	21.0

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Preliminary Results

Net Present Value vs Discounting

Table: Net present value (NPV) NOK in different discount rates in different scenarios

Discount rates	Single species model		Multispecies model	
	Cod	Capelin	Cod	Capelin
No discount ($\delta = 0$)	2.9607e+11	7.4903e+09	3.5070e+11	6.5129e+09
Base case ($\delta = 0.02$)	1.8045e+11	4.7074e+09	2.2003e+11	4.0932e+09
High discount ($\delta = 0.09$)	6.6279e+10	1.6421e+09	7.9374e+10	1.4278e+09

Conclusion so far....

- Capelin or prey must be harvested conservatively in a multispecies model while predator or cod can be harvested at higher rates.
- The NPV is higher for the pulse fishing compared to uniform fishing in cod species.
- Higher discount leads to higher harvest or myopic harvest thus decreasing the stock ??

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Many Thanks for Your Attention

Questions, Comments, Suggestions