Determining Optimal Catch in Age-Structural Multispecies Fisheries

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Background and Motivation

- The Bioeconomic **aggregated biomass models** are very common among fisheries economists, compared to **age structured models**.
- While many researcher or economist think that age structured population models are more realistic models (Wilen 2000).
- Tahvonen (2008, 2009) compared both models and found that optimal policy in ASM may yield fruitful insights and increase the contribution in the resource management.
- In the age structured model, there are individual parameters (or functions) for all biological phenomena, unlike lumped parameters in the biomass model. But, simulation approach dominates optimization approach.

Background and Motivation

- Due to the increasing possibility of optimization, the age-structured models are gaining more and more popularity (Steinshamn, 2011; Tahvonen, 2011).

- However, **multi-species** optimization model are still rare due to the unavailability of the analytical solution and optimization is difficult due to increase in the variables and functions.

- Given the significance of ASM, we develop ASM in multi-species settings for Barents sea cod and capelin.

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Background and Motivation

This work is based on some specific literatures.

- Tahvonen et al. (2013) discuss optimal harvesting strategy in a single species age structured model.

- Steinshamn (2011) which is theoretical paper that include the density dependency in the model.

Objective of the Paper

The objective is to determine the optimal catch in **multi-species** fisheries that include **density dependency** in the harvest. An empirical application of theoretical model by Steinshamn (2011) and extension of Tahvonen et al (2013) in multispecies setting.

Model

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

The optimization/maximization is subjected to stock/population dynamics, effort restriction and sustainability constraints.

As mentioned earlier, we include the stock density dependency in the model.

Recruitment (number) is estimated using Beverton-Holt recruitment function.

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:

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

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

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

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Model

The stock dynamics x and y can be given as:

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

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

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, k_y, $M_{x,a}$ and $M_{y,a}$ are age specific parameters
$k_x h_x E_{x,t}$ and $k_y h_y E_{y,t}$ are fishing mortality of species x, y.

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

Model

The restriction on Effort is given as:

$$E_{x,t}^{max} = \frac{N_{x,a,t}^{1-\alpha} M_{x,a}}{k_x h_x [\exp(M_{x,a}(1-\alpha))]} \tag{4}$$

$$E_{y,t}^{max} = \frac{N_{y,a,t}^{1-\alpha} M_{y,a}}{k_y h_y [\exp(M_{y,a}(1-\alpha))]} \tag{5}$$

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**).

Data and Numerical Application

- The model is applied to cod and capelin fishery in the Barents Sea.
- Cod is a demersal fishery and **uniformly** distributed that is the density of the fish is proportional to the abundance of the fish. While capelin is a pelagic **schooling** fishery, density remain constant as the stock size or the abundance of the fish varies.
- Data are obtained from ICES.
- We employ Knitro, a non linear solver, integrated with Matlab software for numerical optimization.
- The optimization horizon is 50 years.

Parameters and Initial Values

- Most of the Biological parameters and initial values were directly obtained from ICES, some were estimated using the same data source.
- The economic parameters such as price and costs are taken from Fiskeridirektoratet (2011), some parameters are taken granted such as discount rate or density dependency.
- Age Groups: Capelin population is categorized in 4 different age groups, and the cod stock is in 11 age groups.

Parameters and Initial Values

Table 1: Biological parameters and initial values of capelin species

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 ICES data during 1972- 2012
Age specific selectivity parameter $k_{x,a}$	[0.4 0.6 01 01]	Steinshamn (2010)
Age specific density parameter $h_{x,a}$	[0.81 0.81 0.81 0.81]	Steinshamn (2010)

Parameters and Initial Values

Table 2: Biological parameters and initial values of cod species

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 ICES data during 1946-2012
Age specific selectivity parameter $k_{y,a}$	[0.4 0.6 08 01 01 01 01 01 01 01 01]	Steinshamn (2010)
Age specific density parameter $h_{y,a}$	[0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8]	Steinshamn (2010)

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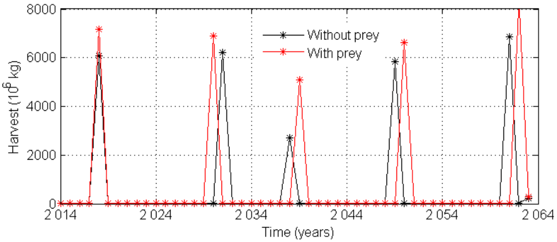
Parameters and Initial Values

Table 3: Economic parameters used in optimization of the model

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

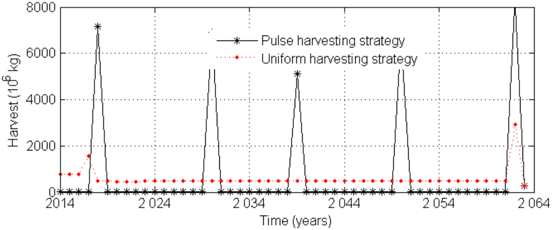
Optimal Harvest Policy for Cod



- Periodic or pulse fishing. Similar pattern as in Hannesson (1975); Tahvonen (2011) and others.
- The optimal catch for cod should be lower when there is no prey, capelin, in the ecosystem. This is intuitive because in the single species setting, there is lack of food for cod which may lead to a lower total biomass of the cod.

Preliminary Results

Pulse Fishing vs Uniform Fishing in cod



- Fishing interval is found approximately ten years, which seems unrealistic in the real world fisheries management.
- The uniform fishing strategy, which can be the second best policy, as it leads to lower revenues than the periodic fishing strategy. A similar result as in Da-Rocha et al. (2012).

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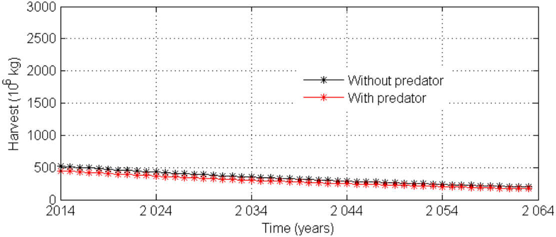
Preliminary Results

Optimal Harvest Policy for Capelin



- When there is predator in the ecosystem, a conservative harvest becomes optimal compared with the model that do not consider predator in the ecosystem.

Preliminary Results

Net Present Value: Single species Model vs Multispecies Model

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

Scenarios	Cod Speceis	Capelin Species	Total
Single species model	180450	4707.4	185160
Multispecies model	220030	4093.2	224120
Difference	39580	614.2	38966
Change (%)	21.9	13.0	21.0

- Table shows that the NPV of the fishery over the 50 years of period in different model settings.
- Higher NPV in multi-species settings.

Preliminary Results

Net Present Value vs Discounting

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

Discount rates	Single species model		Multispecies model	
	Cod	Capelin	Cod	Capelin
No discount ($\delta = 0$)	296070	7490	350700	6512.9
Base case ($\delta = 0.02$)	180450	4707	220030	4093.2
High discount ($\delta = 0.09$)	66279	1642	79374	1427.8

- NPV of the fishery is decreasing with increasing discount rate, as expected.
- The effect of discounting is decreasing with increasing discount rate.

Conclusion so far....

- Empirically tested a theoretical model with density dependency in the harvest function and found that the result is representative of the real world fishery.
- NPV is higher for the model with predator-prey interactions.
- The NPV is higher for the pulse fishing compared to uniform fishing in cod species.
- Capelin or prey must be harvested conservatively in a multispecies model while predator or cod can be harvested at higher rates.
- Higher discount leads to higher harvest or myopic harvest thus decreasing the stock ??

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