Adaptive harvest under invasive induced mortality

Jon Olaf Olaussen* ,Yajie Liu**, Anders Skonhoft***

*Trondheim Business School

**Sintef Fisheries & Aquaculture

***Department of Economics, NTNU

Wild salmon: Ecological problems

- Farmed salmon: Cross breeding (hybrids)
  - Genetic pollution
  - Destroying spawning nests
- Spread of deceases
  - Furunculosis
  - Gyrodactylus salaris
- Farmed salmon: Salmon lice (Lepeophtheirus)

Recent years:

- Salmon lice density
- Increased by aquaculture
  - Heuch et al 2005
- Smolt on out-migration journey
  - Have to pass fish farms
- More than 10 salmon lice per smolt: certain death
  - Revie et al 2009

Invasive?

- Salmon lice
  - Native
- Dominant colonization of habitat
  - Due to human action (fish farming)
  - Disturbing the balance of species

Main solutions:

1. Farming sector: Reduce sea lice density in fish farms?
   - Resistance to treatment
2. Wild sector: Reduce fishing mortality?
3. Wild sector: Change harvesting pattern?

The model

- Three mature age classes:
- 1 Sea-winter (1SW)
  - <3kg
- 2 Sea-winter (2SW)
  - 3-7kg
- 3 Sea-winter (3SW)
  - >7kg

Why age class model?

- Previous management: Uniform harvest rate across stages (”a salmon is a salmon”)
- Recent management trend: Stage specific harvest
  - Catch and release
  - «No take» of 2 and 3 SW
  - Bag limits for 1, 2 and 3SW

Anectodical background

- Salmon anglers want to kill ”all” 1SW salmon
- Common view:
  - 1SW salmon does not contribute to spawning (about 80% is male)
  - Should harvest most 1SW, less 2SW and even less 3SW
- Will the model confirm?

The overall aim

- Look at different harvest regimes for wild salmon
- Uniform harvest rate versus stage specific harvest rate
- Stage specific harvest rates versus fixed uniform harvest rates
- Harvest (use) values versus non-use values

Lagrangian

$$L = [p_4 w_4 s_3 \sigma f_4 + p_5 w_5 s_3 (1-\sigma)\varphi s_4 f_5 + p_6 w_6 s_3 \left(1-\sigma-\varphi+\varphi\sigma\right) s_4 s_5 f_6]N_3$$

$$-\lambda[N_3 - sR(B)]$$

$$-\mu\{B-[\gamma_4 s_3 \sigma(1-f_4)+\gamma_5 s_3(1-\sigma)\varphi s_4(1-f_5)+\gamma_6 s_3\left(1-\sigma-\varphi+\varphi\sigma\right)s_4 s_5(1-f_6)]N_3\}$$

FOC:

$$\partial L / \partial f_4 = N_3(p_4 w_4 - \mu\gamma_4) \underset{<}{\overset{\geq}{-}} 0 \qquad 0 \leq f_4 \leq 1 \qquad (1SW)$$

$$\partial L / \partial f_5 = N_3(p_5 w_5 - \mu\gamma_5) \underset{<}{\overset{\geq}{-}} 0 \qquad 0 \leq f_5 \leq 1 \qquad (2SW)$$

$$\partial L / \partial f_6 = N_3(p_6 w_6 - \mu\gamma_6) \underset{<}{\overset{\geq}{-}} 0 \qquad 0 \leq f_6 \leq 1 \qquad (3SW)$$

- Biomass-value ($p_i w_i$) – fecundity (γ_i) ratio

$$p_i w_i / \gamma_i \qquad\qquad i = 4, 5, 6$$

Norwegian salmon data give:

$$p_4 w_4 / \gamma_4 > p_6 w_6 / \gamma_6 > p_5 w_5 / \gamma_5$$

Possible harvest patterns:

vi) $f_4 = 1,\ f_6 = 1,\ \ 0 < f_5 < 1$

vii) $f_4 = 1,\ f_6 = 1,\ \ f_5 = 0$

viii) $f_4 = 1,\ 0 < f_6 < 1,\ \ f_5 = 0$

ix) $f_4 = 1,\ f_6 = 0,\ \ f_5 = 0$

x) $0 < f_4 < 1,\ f_6 = 0,\ \ f_5 = 0$

Table 2: Optimal fishing mortalities under different sea lice induced mortality levels

	f_4	f_5	f_6	N_3	B	H_4	H_5	H_6	π
Baseline	1	0.52	1	1663	494	358	68	53	**5,517**
s=0.04	1	0.46	1	1299	431	279	47	41	**4,206**
s=0.03	1	0.38	1	933	359	202	28	30	**2,932**
s=0.02	1	0.24	1	587	275	126	11	19	**1,718**
s=0.01	1	0	0.98	240	151	52	0	8	**617**
s=0.005	1	0	0.30	90	79	19	0	1	**170**
s=0.1	**1**	**0.66**	**1**	**3524**	**740**	**758**	**182**	**113**	**12,380**

Note: f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population while B is the spawning population. H_4, H_5, and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively while π is the yearly profit in NOK 1000. s is the lumped survival rate from the juvenile to the smolt stage.

Table 3: Optimal uniform fishing mortality under different sea lice induced mortality levels

	f_4	f_5	f_6	N_3	B	H_4	H_5	H_6	π
Baseline	0.80	0.80	0.80	1593	391	273	99	41	**5,058**
s=0.04	0.77	0.77	0.77	1236	339	205	75	31	**3,806**
s=0.03	0.74	0.74	0.74	884	280	140	51	21	**2,600**
s=0.02	0.68	0.68	0.68	542	210	79	29	12	**1,467**
s=0.01	0.54	0.54	0.54	218	120	26	9	4	**474**
s=0.005	0.36	0.36	0.36	71	55	10	28	17	**101**
s=0.1	**0.86**	**0.86**	**0.86**	**3424**	**594**	**630**	**229**	**94**	**11,690**

Note: f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population while B is the spawning population. H_4, H_5, and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively while π is the yearly profit in NOK 1000. s is the lumped survival rate from the juvenile to the smolt stage.

Table 4: Fixed uniform fishing mortality under different sea lice induced mortality levels

	f_4	f_5	f_6	N_3	B	H_4	H_5	H_6	π
Baseline	0.80	0.80	0.80	1593	391	273	99	41	**5,058**
s=0.04	0.80	0.80	0.80	1193	294	204	74	30	**3,788**
s=0.03	0.80	0.80	0.80	793	195	136	50	20	**2,520**
s=0.02	0.80	0.80	0.80	393	97	67	25	10	**1,249**
s=0.01	0.80	0.80	0.80	0	0	0	0	0	**0**
s=0.005	0.80	0.80	0.80	0	0	0	0	0	**0**
s=0.1	**0.80**	**0.80**	**0.80**	**3593**	**884**	**615**	**224**	**92**	**11,410**

Note: f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population while B is the spawning population. H_4, H_5, and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively while π is the yearly profit in NOK 1000. s is the lumped survival rate from the juvenile to the smolt stage.

Conclusion 1:

- Stage specific versus optimal uniform harvest rate
  - Profits increases by 9-70%
- Stage specific versus fixed uniform harvest rate
  - Fixed may lead to exctinction

Management:

- Harvest 1SW, then 3SW and eventually 2SW
- Hence, general angler opinion:
  - Correct with respect to 1SW
  - Wrong with respect to 2SW versus 3SW

Extension: Adding non-use values

- Maximizing social sustainable value: W
  - Harvest value (Y) + Non-use value (Q)

$$W = \alpha U(Y) + (1-\alpha)V(Q)$$

- U(Y) and V(Q) both concave with α as the weighting factor
- Above results: α=1

$$
\begin{aligned}
L = {} & \alpha[U\left((z_4 w_4 s_3 \sigma f_4 + z_5 w_5 s_3 (1-\sigma)\varphi s_4 f_5 + z_6 w_6 s_3 \left(1-\sigma-\varphi+\varphi\sigma\right) s_4 s_5 f_6) N_3\right)] \\
& +(1-\alpha)\left[V\left((w_4 s_3 \sigma (1-f_4) + w_5 s_3 (1-\sigma)\varphi s_4 (1-f_5) + w_6 s_3 \left(1-\sigma-\varphi+\varphi\sigma\right) s_4 s_5 (1-f_6)) N_3\right)\right] \\
& -\lambda[N_3 - sR(B)] \\
& -\mu\{B - [\gamma_4 s_3 \sigma (1-f_4) + \gamma_5 s_3 (1-\sigma)\varphi s_4 (1-f_5) + \gamma_6 s_3 \left(1-\sigma-\varphi+\varphi\sigma\right) s_4 s_5 (1-f_6)] N_3\} \qquad ,
\end{aligned}
$$

(9') $$w_4 / \gamma_4 \overset{\geq}{\underset{<}{=}} \mu / [\alpha U'(.) z_4 - (1-\alpha) V'(.)]$$

(10') $$w_5 / \gamma_5 \overset{\geq}{\underset{<}{=}} \mu / [\alpha U'(.) z_5 - (1-\alpha) V'(.)]$$

(11') $$w_6 / \gamma_6 \overset{\geq}{\underset{<}{=}} \mu / [\alpha U'(.) z_6 - (1-\alpha) V'(.)]$$

Table 2: Managing for harvest value only ($\alpha = 1$). Optimal fishing mortalities under different sea lice-induced mortality levels.

	f_4	f_5	f_6	N_3	H_4	H_5	H_6	U	V	W
s=0.05	1	0.52	1	1,663	358	68	53	3.808	1.884	3.808
s=0.04	1	0.46	1	1,299	279	47	42	3.535	1.755	3.535
s=0.03	1	0.38	1	933	202	28	30	3.175	1.568	3.175
s=0.02	1	0.24	1	587	126	11	19	2.641	1.301	2.641
s=0.01	1	0	0.98	240	51	0	8	1.618	0.698	1.618
s=0.005	1	0	0.30	90	19	0	1	0.282	0.088	0.282

Note: s is the lumped survival rate from the juvenile to the smolt stage where *s=0.05* is the survival rate in absence of sea lice. f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population. H_4, H_5, and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively, while U is the utility in the recreational fishery, V is the non-consumptive utility and W is the weighted social welfare (U,V and W all measured in 100 000 NOK). 1NOK=0.17USD (Aug. 21 2013)

Table 3: Managing for harvest and non-consumptive values ($\alpha = 0.5$). Optimal fishing mortalities under different sea lice-induced mortality levels.

	f_4	f_5	f_6	N_3	H_4	H_5	H_6	U	V	W
s=0.05	1	0	0.31	1,886	405	0	19	3.372	3.148	3.260
s=0.04	1	0	0.29	1,287	320	0	14	3.124	2.920	3.022
s=0.03	1	0	0.25	1089	234	0	9	2.791	2.627	2.709
s=0.02	1	0	0.17	692	149	0	4	2.292	2.211	2.252
s=0.01	1	0	0	299	64	0	0	1.350	1.445	1.398
s=0.005	0.94	0	0	100	20	0	0	0.195	0.391	0.293

Note: f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population. H_4 , H_5 , and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively, while *U* is the utility in the recreational fishery, *V* is the non-consumptive utility and *W* is the weighted social welfare. s is the lumped survival rate from the juvenile to the smolt stage where *s=0.05* is the survival rate in absence of sea lice.

Table 6: Managing for harvest and non-consumptive values ($\alpha = 0.5$). Optimal uniform fishing mortality under different sea lice-induced mortality levels.

	f_4	f_5	f_6	N_3	H_4	H_5	H_6	U	V	W
s=0.05	0.46	0.46	0.46	1,846	183	67	27	3.322	3.152	3.237
s=0.04	0.45	0.45	0.45	1,448	141	51	21	3.062	2.924	2.993
s=0.03	0.44	0.44	0.74	1,052	99	36	15	2.711	2.630	2.670
s=0.02	0.41	0.41	0.41	659	58	21	9	2.179	2.209	2.194
s=0.01	0.34	0.34	0.34	274	20	7	3	1.115	1.443	1.279
s=0.005	0.23	0.23	0.23	92	4	2	1	0.004	0.512	0.258

Note: f_4, f_5 and f_6 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_3 is the potentially harvestable population. H_4, H_5, and H_6 are the harvest (in number of salmon) of the 1SW, 2SW, and 3SW, respectively, while U is the utility in the recreational fishery, V is the non-consumptive utility and W is the weighted social welfare. s is the lumped survival rate from the juvenile to the smolt stage where *s=0.05* is the survival rate in absence of sea lice.

Conclusion 2:

- Adding non-use values:
  - Harvest pattern less aggressive
  - Stage specific versus optimal uniform harvest rate
    - Profits increases by 1-14% (9-70%)
- Stage structured harvest dampens effect of invasive induced mortality
  - But less when non-use values are included