8. Adaptive harvest strategies in the case of invasive species-induced mortality

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8.1 Abstract

This chapter considers adaptive harvest strategies under invasive species-induced mortality. The overall aim is to analyze how the harvest regimes and utility obtained from wild Atlantic salmon change when external factors, such as invasive species-induced mortality, reduce the wild stock survival. The wild salmon stock is associated with both use and non-use values. We have considered two types of adaptive harvest regimes when the salmon is faced with negative consequences from invasive interaction. The first is a selective harvest regime, where the trade-off between the harvest value and the contribution to the recruitment of the stock is taken into account. This harvest regime is contrasted with the traditional uniform harvest pattern across different age classes. We find that the selective type harvest pattern is more important the more important the harvest value is in the social welfare function.

- *Keywords*: Atlantic salmon, invasive, Artic, age-structured model, social welfare.
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8.2 Introduction

Man-made activities frequently provide challenges for both terrestrial as well as aquatic species. The most well-known examples are pollution, deforestation, habitat degradation, overfishing and introduction of invasive species. One of the challenges facing management in the Artic is invasions. Invasive species may establish in the Artic accidentally due to e.g. ballast water or escapement from aquaculture, intentionally by deliberate introduction or due to habitat alterations associated with climate change. Some changes are hence possible to influence, while others can hardly be influenced. In the same manner, some changes may have huge consequences while in other cases, it may be possible to diminish the consequences to man by adaptation.

In this chapter, we look at the case of wild Atlantic salmon (*Salmo salar*) harvest under invasive species-induced mortality. Atlantic salmon harvest serves as a good example of a species living within the Artic habitat being vulnerable to invasive species for a number of reasons. As for many Artic species, the potential invader challenges are numerous. Climate change may alter the survival rate in the offshore habitat, inducing introduction of new species competing for the food, or predating directly on the salmon. Salmon farming also increases the wild salmon mortality through increased spawning competition from escapements, destruction of wild salmon spawning nests in the rivers, spread of diseases as well as increased sea lice density.

Atlantic salmon stocks have declined during the last decades. A recent report from the scientific advisory board for salmon management in Norway states that the high sea lice densities, together with escaped farmed salmon from aquaculture, are the two most significant and existential threats to the wild salmon populations in Norway (Anon 2011). Salmon aquaculture increases the sea lice density in the fjords and along the coast because it amplifies the number of hosts for the lice by a magnitude of 100 (Heuch *et al*. 2005). Aquacultured salmon is considered an invasive itself since it is genetically different from any of the wild salmon stocks due to the special breeding program for farmed salmon.

In this chapter we apply an age-structured wild salmon population model to assess the welfare loss of the invasive species-induced mortality. The economic losses and effects on the fishing mortalities are analyzed by obtaining the reduced harvesting value of the mature salmon due to various invasive induced mortality scenarios.[2] First, we analyze what happens when the wild salmon manager aims to maximize the social sustainable value of the wild stock consisting of harvest plus stock value under selective harvesting of the different age classes. Then, in a next step, we analyze the situation in which a uniform fishing mortality rate is applied across the different age classes.

[2] In the fisheries literature, fishing mortalities refer to harvest rates.

The reason for analyzing these different harvest strategies is that, during the last decade, the management regime of the wild Atlantic salmon in Norway has gradually shifted from one in which a fish is considered "just a fish" towards one with a selective harvesting pattern for each year class of mature salmon (Thorstad *et al*. 2001). This is made possible by allowing for catch and release management; that is, a regime in which the angler can release the salmon if the bag limit for that specific year class of salmon (measured by size) is met. This has also made it possible to allow angling for, e.g., the smallest type of mature salmon; that is, salmon less than 3 kg, or the so called 1SW, while all older (bigger) salmon must be released.[3] This new potential flexibility in management has however not yet been put fully into effect, and the difference in management practice among rivers is large. This may possibly hinge on the lack of analysis of what the best harvest regime would look like under different mortality levels. The overall aim of this chapter is hence to assess the welfare loss of increased mortality under different scenarios, and to explore to what extent the optimal adaptive harvesting policy is affected by invasive-induced mortality.

Both fishery ecologists (e.g., Hilborn and Walters 2001; Walters and Martell 2004) and economists (e.g., Wilen 1985; Townsend 1986) have argued that management models should be based on age- and/or -stage-structured biological models instead of the simplified biomass models. Due to the complexity of age structured models, economic studies based on such models have basically been case studies illustrated by numerical analysis. One noteworthy exception is Tahvonen (2009), who demonstrates analytical results on optimal harvesting under certain simplifying assumptions within a dynamic framework. In addition, Skonhoft *et al*. (2012) analyzed a static maximum economic yield fishery with three age classes under perfect and imperfect selectivity, and demonstrated several analytical results that contrast what are found in the biomass models. In closer relation to the present study, Massey *et al*. (2006) developed a stage-structured bioeconomic model of the recreational Atlantic coast summer flounder fishery. They look at the benefits of improving the water quality conditions in Maryland`s coastal bays. When the benefits are compared with estimates from a non-structural model, they find that the unstructured model is likely to lead to inaccurate predictions.

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[3] 1SW are salmon that have stayed 1 winter (e.g. 1 sea winter) in the offshore habitat before they return to spawn in the river. Further, 2SW and 3SW have stayed 2 and 3 winters, respectively, before spawning migration.

This study is structured as follows. The next section presents the population model and welfare function associated with the wild salmon. Then, a numerical illustration applying Norwegian salmon data is presented. Some concluding remarks and management implications are given in the final section.

8.3 Population model and welfare function

8.3.1 Atlantic salmon

Atlantic salmon is an anadromous species with a complex life cycle that includes several distinct phases. Freshwater habitat is essential for the early development stages, where it spends the first 1–4 years from spawning to juvenile rearing, before undergoing smoltification and seaward migration. It then stays from 1–3 years feeding and growing in the ocean, and, when mature, it returns to its natal, or "parent", rivers to spawn in the spring and/or summer. A fraction of the stock returns to spawn after only one winter in the offshore habitat. This is the 1SW (Sea winter) sub-population that is typically 1–3 kg. Another fraction returns after two winters, the 2SW sub-population that is typically between 3–7 kg. The remaining part of the stock returns after three winters, the 3SW sub-population that is typically above 7 kg. After spawning in autumn, most salmon die, as less than 10% of the female salmon spawn twice (Mills 2000). The Atlantic salmon is subject to fishing when it migrates back to its parent river. In Norway, sea fishing takes place in fjords and inlets with wedge-shaped seine and bend nets, and is commercial or semi-commercial. In the rivers, salmon are caught by recreational anglers with fishing rods. The recreational fishery is the far most important from an economic point of view (NOU 1999), but in number and biomass of fish caught, these two fisheries are today more or less equivalent (Anon. 2011; Liu *et al*. 2011). More than half of the present commercial catch is caught in the Finnmark County, while in the remaining 18 counties, the commercial harvest is already shut down or rapidly decreasing due to strict regulations (Statistics Norway 2011). In the following, we assume all harvest takes place in the rivers. There are two main reasons for this. First, due to strict regulations of the marine salmon fishery since 2008, sea fishing seems to gradually be fading away, and is already non-existent in many fjords (Statistics Norway 2011). Second, we want to look at the most valuable harvest pattern, and it is well known that this involves zero marine harvest (see e.g. Olaussen 2007; Liu *et al*. 2011).

8.3.2 Welfare

Atlantic salmon may be valued both for use as well as non-use values. In the following, we consider the recreational harvest value (use value) and the intrinsic stock value (non-use value). The utility from recreational harvest of salmon is given by the utility function $U(Y_t)$. In general, the utility from harvest is a measure of the value of the catches, accounting for differences in the weights, values, and catchability of the different year classes of salmon. Readers that are not particularly interested in the specific model details may now move to the numerical illustration section. In the utility function, Y_t is the year class scaled biomass harvested (in kg) in year t. With w_3, w_2, and w_1 as the fixed weights (kg per fish, with $w_3 > w_2 > w_1$) and f_3, f_2, and f_1 as the harvest fractions of the 3SW, 2SW, and 1SW mature population, respectively, the biomass harvested (in kg) in year t is defined by

$$y_t = w_1 s_1 \sigma f_{1,t} N_{0,t} + w_2 s_1 (1-\sigma)\varphi s_2 f_{2,t} N_{0,t-1} + w_3 s_1 \left(1-\sigma-\varphi+\varphi\sigma\right) s_2 s_3 f_{3,t} N_{0,t-2}$$

Here, the fraction of the stock that returns after one winter at sea is σ, and hence $(1-\sigma)\varphi$ is the fraction that returns after two winters at sea and $(1-\sigma-\varphi+\varphi\sigma)$ is the fraction that returns after three sea winters. Finally, N_0 is the number of recruits that make it to the offshore habitat, and s_1, s_2 and s_3 are the stage-specific survival rates respectively. The utility obtained from different year classes may typically differ. For example, recreational anglers may prefer harvest of 3SW salmon over 2SW salmon and 2SW over 1SW. This could be due to the trophy aspect of the fishing experience (see Nævdal *et al*. 2012). To allow for different valuation of different age classes, we have the scaling parameter z_i $(i = 1, 2, 3)$ for each of the year classes in the harvest, and hence the year class scaled biomass harvested is written

$$Y_t = z_1 w_1 s_1 \sigma f_{1,t} N_{0,t} + z_2 w_2 s_1 (1-\sigma)\varphi s_2 f_{2,t} N_{0,t-1} + z_3 w_3 s_1 \left(1-\sigma-\varphi+\varphi\sigma\right) s_2 s_3 f_{3,t} N_{0,t-2}$$

Note that since the scaling parameters for the different year classes, z_i, are determined by the preferences for salmon in the recreational fishery, we typically have $z_3 \geq z_2 \geq z_1$ (Olaussen and Liu 2011).

The non-harvest related utility obtained from the stock is given by the utility function $V(Q_t)$ where

$$Q_t = w_1 s_1 \sigma (1-f_{1,t}) N_{0,t} + w_2 s_1 (1-\sigma)\varphi s_2 (1-f_{2,t}) N_{0,t-1} + w_3 s_1 \left(1-\sigma-\varphi+\varphi\sigma\right) s_2 s_3 (1-f_{3,t}) N_{0,t-2}$$

represent the stock (in kg) after harvest has taken place. Both $V(Q_t)$ and $U(Y_t)$ are assumed to be increasing and concave functions, that is, a higher salmon stock as well as a higher harvest yields a higher utility, but at a declining rate.

We next formulate a welfare, or utility, function that takes both the conservation and the use perspective of salmon into account (see Liu *et al*. 2013). The utility provided through harvesting salmon (use value) and the utility derived from the intrinsic value (non-use-value) the wild salmon stock possesses are both included in the social welfare function $W_t = W[U(Y_t), V(Q_t)]$. When assuming separability, the social welfare at time t can be written $W_t = \alpha[U(Y_t)] + (1-\alpha)[V(Q_t)]$.

The parameter $0 \leq \alpha \leq 1$ is a weighting factor between use and non-use values. Hence, if $\alpha = 1$, only harvest counts in the welfare function, while $\alpha = 0$ implies that only the intrinsic value is taken into account. Consequently, $\alpha = 0.5$ indicates an equal valuation of harvest and stock abundance.

8.4 A Numerical illustration

The specific biological and economic model is quite complex.[4] For the specific purpose of this chapter, it is sufficient to acknowledge that the model is solved by maximizing the social welfare in equilibrium, that is, a situation in which no one has incentive to change their behavior. Further, the Kuhn-Tucker first order conditions that define the optimization provide easily interpreted equations. It turns out that for the Norwegian data, straightforward harvest patterns are revealed as long as we assume that the recreational anglers are indifferent with respect to which year class they harvest. In this case, only the biomass/fecundity ratio w_i / γ_i $(i = 1,2,3)$ steer the fishing mortality and the fishing composition, and hence no other factors play a *direct* role. Here w_i is the average weight of the year class i while γ_i is the average fecundity of the same year class. The intuition behind these relative ratios is that they determine the relative economic (through the weights, w_i) versus the biological (through the fecundities, γ_i) of the different year classes. For the wild Atlantic salmon, the data give us the following relationship: $w_1 / \gamma_1 > w_3 / \gamma_3 > w_2 / \gamma_2$, which determines the optimal harvest pattern. By harvest pattern, we mean year classes that are harvested, and to what extent. Generally, the Kuhn-Tucker first order conditions give us thirty different potential harvest patterns. For example, when we have

[4] Both the model specification and parameter values are available on authors request.

$w_1/\gamma_1 > w_3/\gamma_3 > w_2/\gamma_2$, which is in accordance with our Norwegian wild salmon data, there will be five potential harvest patterns given by i) $f_1=1,\ f_3=1,\ 0<f_2<1$, ii) $f_1=1,\ f_3=1,\ f_2=0$, iii) $f_1=1,\ 0<f_3<1,\ f_2=0$, iv) $f_1=1,\ f_3=0,\ f_2=0$, v) $0<f_1<1,\ f_3=0,\ f_2=0$.[5]

Clearly, the most aggressive harvest pattern is given by case i), where the whole 1SW and 3SW sub populations are harvested. Then, harvest pattern ii) is less aggressive, and so on, with harvest pattern v) giving the lowest harvesting pressure; that is, only harvesting some proportion of the 1SW.

8.4.1 Results

Managing for harvest value only, $\alpha=1$

First, we look at the harvest pattern when the manager is concerned with the use value only (harvest value).With weight–fertility variations as $w_1/\gamma_1 > w_3/\gamma_3 > w_2/\gamma_2$, we find that the potential optimal fishing mortality possibilities under the assumption of perfect fishing selectivity are given by cases i) - v) as described above. In the baseline scenario, we find that case i) with $f_1 = f_3 = 1$ and $f_2 = 0.52$ yields the optimal fishing mortality pattern. See Table 1 (first column). Based on valuation data from a typical small Norwegian salmon river, the overall social welfare becomes 3.808 (NOK 100,000), consisting of utility obtained from harvest only (Olaussen 2007, Olaussen and Liu 2011). The consequences of invasive species-induced mortality are also demonstrated in Table 1. It is not possible to give an accurate estimate regarding how much the smolt survival, *s*, is reduced due to invasive induced mortality on a national scale. Note that the smolt mortality takes place before the smolt reaches the offshore winter habitat, and should not be confused with the stage specific mortalities. Hence, the N_0 population from above is the population remaining after the smolt stage. The mortality effect due to invasives varies between fjords, and from river to river. To take this variation into account, we assess the consequences at different mortality levels. When the smolt mortality increases such that the survival rate s decreases, the fishing mortality for 2SW decreases while it is still opti-

[5] The twenty-five remaining possibilities are found by assuming $w_1/\gamma_1 > w_2/\gamma_2 > w_3/\gamma_3$, $w_2/\gamma_2 > w_3/\gamma_3 > w_1/\gamma_1$, $w_2/\gamma_2 > w_1/\gamma_1 > w_3/\gamma_3$, $w_3/\gamma_3 > w_2/\gamma_2 > w_1/\gamma_1$, and $w_3/\gamma_3 > w_1/\gamma_1 > w_2/\gamma_2$.

mal to keep $f_1 = f_3 = 1$ at the 40% smolt survival reduction (s=0.03), and we hence have pattern i) as described above. With this survival rate, the utility is reduced by about 17% to 3.175 (NOK 100,000). The same harvest pattern is kept even for a 60% reduction in the smolt survival ($s = 0.02$). In this case, the utility is reduced significantly and is now only 1718 (NOK 1,000), that is, about one third of the profit in the baseline scenario. With an 80% reduction in the baseline smolt survival rate and $s = 0.01$, we find that it is still optimal to harvest the whole 1SW stage population, while the harvest of the 3SW is reduced to $f_3 = 0.98$, and there is no harvest of 2SW fish. We then have the above described pattern iii). The same case is still present when the smolt survival is further reduced to $s = 0.005$. Note that the N_0 harvestable population decreases relatively more than the social welfare for all reductions in the survival parameter since the marginal utility is decreasing in number of fish (concave social welfare function). As a result, the utility is reduced less; that is, the social welfare is reduced by about 42% (1618) when the survival rate is reduced by 80% (s=0.01).

It may seem surprising that even when the smolt survival is reduced by 90%, the harvest is still quite aggressive. The reason is that the recruitment function is very steep at low stock levels. However, it may be shown that the shape of the recruitment function must be altered quite significantly before the second most aggressive harvest pattern (pattern ii)) replaces the most aggressive (pattern i)).

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

	f_1	f_2	f_3	N_0	H_1	H_2	H_3	U	V	W
s=0.05	1	0.52	1	1663	358	68	53	3.808	1.884	3.808
s=0.04	1	0.46	1	1299	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_1, f_2 and f_3 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_0 is the potentially harvestable population. *H*$_1$, *H*$_2$, and *H*$_3$ 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 NOK 100,000). NOK 1 = USD 0.17 (Aug. 21 2013).

Managing for harvest and stock value, $\alpha = 0.5$

As expected, when the manager takes both harvest and the stock value (non-consumptive value) into account, the optimal harvest pattern is less aggressive. In the baseline case, we have the harvest pattern iii) from above with $f_1 = 1,\ f_3 = 0.31, \text{and } f_2 = 0$. If natural mortality is reduced by 80% (s=0.01), we have harvest pattern iv) with $f_1 = 1,\ f_3 = 0, \text{and } f_2 = 0$. Finally, a further reduction of the natural mortality, s=0.005, gives the harvest pattern v) from above with $f_1 < 1,\ f_3 = 0, \text{and } f_2 = 0$. Not surprisingly, when use and non-use values are weighted equally, the stock will be higher, while the harvest, and hence the harvest value, will be lower.

Table 2: Managing for harvest and non-consumptive values ($\alpha = 0.5$). Optimal fishing mortalities under different invasive-induced mortality levels

	f_1	f_2	f_3	N_0	H_1	H_2	H_3	U	V	W
s=0.05	1	0	0.31	1886	405	0	19	3.372	3.148	3.260
s=0.04	1	0	0.29	1287	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: 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_1, f_2 and f_3 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_0 is the potentially harvestable population. H_1, H_2, and H_3 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 NOK 100,000). NOK 1 = USD 0.17 (Aug. 21 2013)

Managing for stock value only, $\alpha = 0$

When the manager only takes the stock value of the salmon into consideration, no harvest takes place. Consequently, this is the case where the invasive species-induced mortality has least impact on the stock level. Furthermore, since social welfare is dependent on the stock value only, this is the case where the social welfare reduction is smallest. In this case, due to the concave utility function, an 80% reduction in the survival rate reduces the stock level by 83%, while the social welfare is reduced by less than 50%.

Table 3: Managing for non-consumptive values only ($\alpha = 0$). Optimal fishing mortalities under different invasive-induced mortality levels

	f_1	f_2	f_3	N_0	H_1	H_2	H_3	U	V	W
s=0.05	0	0	0	1917	0	0	0	0	3.808	3.808
s=0.04	0	0	0	1518	0	0	0	0	3.574	3.574
s=0.03	0	0	0	1117	0	0	0	0	3.268	3.268
s=0.02	0	0	0	717	0	0	0	0	2.824	2.824
s=0.01	0	0	0	318	0	0	0	0	2.008	2.008
s=0.005	0	0	0	117	0	0	0	0	1.012	1.012

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_1, f_2 and f_3 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_0 is the potentially harvestable population. H_1, H_2, and H_3 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 NOK 100,000). NOK 1 = USD 0.17 (Aug. 21 2013)

Managing for harvest value only, $\alpha = 1$, optimal uniform harvest rate

Now we turn our attention to the case where the manager does not separate between different age classes, and hence, a uniform harvest rate is applied. As in the cases considered above, the optimal harvest rate is quite high, even for a quite dramatic reduction in the survival rate. For example, a 90% reduction in the survival rate reduces the optimal uniform harvest rate only from 0.80 to 0.36. The social welfare, however, is reduced much more under the uniform harvest rate than in the stage-specific harvest case (0.019 vs. 0.282). Note also that in the baseline case (s=0.05) without invasive species-induced mortality, the social welfare under the uniform harvest rate is only slightly below (2%) the stage-structured harvest pattern.

Table 4: Managing for harvest value only ($\alpha = 1$). Optimal uniform fishing mortality under different invasive-induced mortality levels

	f_1	f_2	f_3	N_0	H_1	H_2	H_3	U	V	W
s=0.05	0.80	0.80	0.80	1593	273	99	41	3.721	2.033	3.721
s=0.04	0.77	0.77	0.77	1236	205	75	31	3.436	1.890	3.436
s=0.03	0.74	0.74	0.74	884	140	51	21	3.055	1.699	3.055
s=0.02	0.68	0.68	0.68	542	79	29	12	2.481	1.412	2.481
s=0.01	0.54	0.54	0.54	218	26	9	4	1.352	0.845	1.352
s=0.005	0.36	0.36	0.36	71	5	2	1	0.019	0.074	0.019

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_1, f_2 and f_3 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_0 is the potentially harvestable population. H_1, H_2, and H_3 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 NOK 100,000). NOK 1 = USD 0.17 (Aug. 21 2013).

Managing for harvest and stock value, $\alpha = 0.5$, uniform harvest rate

A 90% reduction in the survival rate has a relatively modest effect on the uniform harvest rate that is reduced from 0.46 to 0.23. In the case when only the harvest value mattered considered above, the social welfare effect of a uniform harvest rate was quite modest in the baseline case with survival rate s=0.05, and quite substantial when the survival rate was only 0.005. When the stock value matters in the social welfare function, the welfare difference between the uniform and stage-specific harvest rate is much less dramatic. The intuition is straightforward as the more important harvest is in the welfare function, the more impact will a more sophisticated (stage-structured) harvest pattern have compared with a simple uniform harvest pattern.

When it comes to adaptive harvest, both the stage-structured and uniform harvest patterns must be considered adaptive because the harvest rate is changed due to invasive species-induced mortality. In absence of adaptive capacity in the management, that is, if the uniform harvest rate is kept fixed under all invasive species-induced mortality levels, the stock would go extinct.

Table 5: Managing for harvest and non-consumptive values ($\alpha = 0.5$). Optimal uniform fishing mortality under different invasive-induced mortality levels

	f_1	f_2	f_3	N_0	H_1	H_2	H_3	U	V	W
s=0.05	0.46	0.46	0.46	1846	183	67	27	3.322	3.152	3.237
s=0.04	0.45	0.45	0.45	1448	141	51	21	3.062	2.924	2.993
s=0.03	0.44	0.44	0.74	1052	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: 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_1, f_2 and f_3 are harvest rates for the 1SW, 2SW and 3SW class, respectively. N_0 is the potentially harvestable population. H_1, H_2, and H_3 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 NOK 100,000). NOK 1 = USD 0.17 (Aug. 21 2013).

8.5 Concluding remarks

In this paper, we have analyzed one example of the more general class of problems where invasive species provide challenges for native species. The overall aim of this example has been to analyze how the harvest regimes and profitability of wild Atlantic salmon may be changed when external factors, such as invasive species-induced mortality, reduces the natural smolt survival rate. The wild salmon stock is associated with both use and non-use values. We have considered two types of adaptive harvest regimes when the salmon is faced with negative consequences from invasive interaction. The first is a selective harvest regime, where the trade-off between the harvest value and the contribution to the recruitment of the stock is taken into account. This harvest regime is contrasted with the traditional uniform harvest pattern across different age classes. Not allowing different harvest rates for different stages of the salmon stock turns out to reduce the welfare considerably, and seems to be more important the higher the invasive species-induced mortality is. We find that the selective harvest pattern is more important the more important the harvest value is in the social welfare function.

We have found that increased invasive species-induced mortality does not necessarily call for altered harvest regimes, particularly when the mortality reduction was not too strong. In fact, we found surprisingly aggressive harvest patterns to be persistent even under quite high invasive species-induced mortality situations. However, if a fixed uniform fishing mortality is applied, high invasive species-induced mortality may drive the population to extinction. Thus, an optimal selective harvesting regime should be employed to secure both the highest potential welfare and a viable population.

8.6 References

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