



# Conservation versus harvest of wild Atlantic salmon. The cost of sea lice induced mortality



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## ABSTRACT

Increased sea lice densities in the farmed salmon sector have recently led to the growing concerns in Canada, Chile and Norway as the main producer countries. The sea lice incur problems within the farmed fish industry itself as well as in wild stocks. We present a bioeconomic model for wild Atlantic salmon (*Salmo salar*) and explore to what extent the harvest and social benefit of wild salmon fishing in Norway are affected by sea lice-induced mortality. An age-structured population model is required to analyze the losses because the salmon post-smolts are the most vulnerable to attack by sea lice, while the harvest value is related to the three age classes of mature spawning fish. Losses are analyzed by determining the reduced harvesting value as well as the non-consumptive (conservation) value of the wild salmon stock pertinent to various sea lice-induced mortality levels. Our findings indicate that welfare and economic losses in a typical Norwegian salmon river may range from 15 to 25%. In addition, at low sea lice levels, the welfare improvement associated with selective harvest is quite modest, and is even lower when non-consumptive values are deemed important. On the other hand, when sea lice-induced mortality levels are very high, the welfare improvements of selective harvest are substantial.

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## 1. Introduction

We present an analysis of wild Atlantic salmon (*Salmo salar*) management in Norway. The great number of salmon rivers in Norway offers the world's largest spawning ground for Atlantic salmon. Wild salmon has long had significant social, cultural and economic importance for Norwegians. Previously an important food source, today, it is mainly the prized catch for approximately 100,000 recreational anglers that visit these rivers annually. Wild salmon is also valued for its mere existence, as this is a natural treasure that has significant conservation value. Atlantic salmon stocks have declined during the last few decades. One of the most important challenges the wild stocks face is the growing aquaculture industry (NOU, 1999; Fiske et al., 2006; Ford and Myers, 2008; Liu et al., 2011a). The wild population is affected by aquaculture primarily through escaped farmed salmon and by increasing density of sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*). Both these problems emerged soon after the establishment of the farming industry in the 1970s (Heuch et al., 2005). Escaped farmed salmon

interbreed and have genetic interactions with the wild populations. This phenomenon was investigated by Liu et al. (2013) and Hindar et al. (2006), who found that the wild salmon stock is gradually being replaced by salmon with farmed origin. Aquaculture production has also resulted in increased prevalence of sea lice attacks on out-migrating salmon, which is the issue addressed here. In a related study, Liu et al. (2011b) investigated the impacts of sea lice on wild pink and chum salmon fisheries.

The collective term “sea lice” normally refers to a number of copepod crustaceans of the family *Caligidae* (Revie et al., 2009). Sea lice are externally parasitic on the skin of marine and anadromous species. The most common and extensively studied species is the *L. salmonis*, which is a parasite specific to salmonid species. This parasite is prevalent in both Atlantic and Pacific Ocean, and the Chilean farming industry also experiences challenges with *Caligus teres* and *Caligus rogercresseyi* (Revie et al., 2009). The lice are mainly a problem for the salmon post-smolts on their seaward migration journey, as they have to pass the fish farms before they reach their offshore winter habitat. According to the recent report from the scientific advisory board for salmon management in Norway, the high sea lice densities and escaped farmed salmon from aquaculture are the two most significant and existential threats to the wild salmon populations in Norway (Anon, 2014). Salmon aquaculture increases

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the sea lice density in the fjords and along the coast because they amplify the number of hosts for the lice by a factor of 100 (Heuch et al., 2005). Smolt infected by less than 10 sea lice are considered to be unaffected by the parasite. Empirical evidence, however, seems to suggest that this threshold level is too high, as only smolt with 10 lice or fewer survive (Heuch et al., 2005; Holst et al., 2003). In some cases, surveillance studies have revealed that up to 100 sea lice per smolt are not uncommon (Revie et al., 2009). While this evidence is alarming, presently, it is not possible to accurately estimate the reduction in the smolt survival rate due to sea lice-induced mortality on a national scale as the effect varies between fjords, and from one river to another. However, according to some estimates (Anon, 2014), the effect on the smolt survival rate at the national level is considered to be larger, from 25% to 75%. As indicated, other salmon stocks, such as Pacific salmon, are also threatened by sea lice infections, and Krkosek et al. (2007) reported that lice-induced mortality of pink salmon commonly exceeded 80%. Increased sea lice densities may be considered a type of biological pollution and thus a unidirectional externality propagating from the farmed salmon sector to the wild salmon one.

According to Asche (2008), there is little doubt that aquaculture production will continue to expand, allowing the sea lice density to continue to grow as well. Due to this growing concern, in this work, we develop a wild salmon population model that can be applied to assess the economic loss due to sea lice. Because sea lice mainly infect the salmon post-smolt, while the harvest value is related to the mature spawning fish, an age-structured population model is required. The economic losses are analyzed by evaluating the reduced harvest, as well as the reduced conservation value, due to various sea lice-induced mortality scenarios. First, we analyze the case in which the wild salmon manager aims to maximize the welfare under selective harvesting of the different salmon age classes. Next, we compare this harvesting regime with a case where a uniform welfare-maximizing fishing mortality rate is imposed across the different age classes. Finally, we analyze the outcome of the manager maintaining a fixed fishing mortality rate that is not adjusted according to the sea lice-induced mortality level.

These three harvest strategies were chosen for analysis because, during the last decade, the management regime of the wild Atlantic salmon in Norway has gradually shifted from considering fish as “just a fish” towards greater focus on 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 strategy, whereby the angler is supposed to release the salmon if the bag limit of that specific year class of salmon (measured by size) is met. This policy has also enabled angling for the smallest size class, fish less than 3 kg, or the so called 1SW, while mandating release of all older (larger) salmon<sup>1</sup>. However, this new potential management flexibility has not yet been fully implemented, and the differences in management practice between rivers are substantial. Thus, the overall aim of this paper is to assess the welfare loss due to the presence of sea lice under different scenarios, and to explore the extent to which the optimal harvesting policy is affected by sea lice-induced mortality. Therefore, we depart from the work of Liu et al. (2011b) in a number of important aspects, since we study a different salmon species, and focus on recreational instead of commercial fishery. However, the most important difference is that we consider not only harvest values, but also non-consumptive values, in addition to analyzing selective harvest of different age classes.

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-/stage-structured biological models instead of the simplified biomass models. Due to the complexity of age-structured models, most of the extant economic research based on such models has basically involved case studies illustrated by numerical analysis. One noteworthy exception is the work of Tahvonen (2009), who presented analytical results pertaining to optimal harvesting under certain simplifying assumptions within a dynamic framework. Another example of a more comprehensive study is the work of Skonhøft and Gong (2014), who analyzed a salmon model with two mature (harvestable) age classes. An earlier study conducted by Skonhøft et al. (2012) is also relevant for the present investigation, as the authors analyzed a static maximum economic yield fishery with three age classes under perfect and imperfect selectivity conditions. They demonstrated several analytical results that contrast those found in the biomass models.

## 2. Methods

### 2.1. Population model

Atlantic salmon is an anadromous species with a complex life cycle that includes several phases. Freshwater habitat is essential for the early development stages, where this salmon species spends the first 1–4 years from spawning to juvenile rearing, before undergoing smoltification and seaward migration. It spends the subsequent 1–3 years feeding and growing in the ocean. Finally, when mature, it returns to its natal, or “parent”, rivers to spawn in the spring and/or summer. After spawning in autumn, most salmon die, as less than 10% of the female salmon spawn twice (Mills, 1989). Atlantic salmon is subject to fishing when it migrates back to its parent river. Due to strict regulations of the marine salmon fishery that have been imposed in 2008, sea fishing has been gradually reduced, and has ceased in many fjords (Statistics Norway, 2014). In the rivers, salmon are caught by recreational anglers with fishing rods. In the following sections, we assume that all harvest takes place in the river.

In what follows, a specific salmon population (with its native river) is considered in number of individuals at time  $t$  structured as recruits  $N_{0,t}$  ( $\text{yr} < 1$ ); three young age classes,  $N_{1,t}$  ( $1 \leq \text{yr} < 2$ ),  $N_{2,t}$  ( $2 \leq \text{yr} < 3$ ) and  $N_{3,t}$  ( $3 \leq \text{yr} < 4$ ); and three adult spawning classes,  $N_{4,t}$  ( $4 \leq \text{yr} < 5$ ),  $N_{5,t}$  ( $5 \leq \text{yr} < 6$ ), and  $N_{6,t}$  ( $6 \leq \text{yr} < 7$ ). Recruitment is endogenous and density-dependent, and the old spawning salmon have higher fertility than the young spawning salmon (McGinnity et al., 2003). Natural mortality is fixed and density-independent, and, in line with the work of Liu et al. (2013), we assume that the entire spawning population dies after spawning. It is further assumed that the proportion among the three mature age classes remains constant. In fixing this ratio, we imply that a given proportion of the stock returns to spawn after one, two or three years at sea, respectively (see below). A number of factors, such as type of river (“small salmon river” vs. “large salmon river”) and various environmental factors (NOU, 1999) may influence these proportions. As fishing takes place when the fish return to their native river, only the mature salmon stocks  $N_{4,t}$ ,  $N_{5,t}$ , and  $N_{6,t}$  are subject to fishing. A detailed description of the life cycle of the Atlantic salmon can be found in Verspoor et al. (2003).

Denoting the size of the spawning population, adjusted for different fertilities among the three spawning classes (see below) as  $B_t$ , the stock recruitment relationship is first defined by:

$$N_{0,t+1} = R(B_t) \quad (1)$$

where  $R(B_t)$  may be a one-peaked value function (e.g., of the Ricker type) or it may be increasing and concave (e.g., of the Beverton–Holt or Cushing type). In both cases, zero stock implies zero recruitment,

<sup>1</sup> 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.

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