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Quantitative risk assessment of salmon louse-induced mortality of seaward-migrating post-smolt Atlantic salmon

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ABSTRACT

The Norwegian government recently implemented a new management system to regulate salmon farming in Norway, aiming to promote environmentally sustainable growth in the aquaculture industry. The Norwegian coast has been divided into 13 production zones and the volume of salmonid production in the zones will be regulated based on salmon lice effects on wild salmonids. Here we present a model for assessing salmon louse-induced mortality of seaward-migrating post-smolts of Atlantic salmon. The model quantifies expected salmon lice infestations and louse-induced mortality of migrating post-smolt salmon from 401 salmon rivers draining into Norwegian coastal waters. It is assumed that migrating post-smolts follow the shortest path from river outlets to the high seas, at constant progression rates. During this migration, fish are infested by salmon lice of farm origin according to an empirical infestation model. Furthermore, louse-induced mortality is estimated from the estimated louse infestations. Rivers draining into production zones on the West Coast of Norway were at the highest risk of adverse lice effects. In comparison, rivers draining into northerly production zones, along with the southernmost production zone, were at lower risk. After adjusting for standing stock biomass, estimates of louse-egg output varied by factors of up to 8 between production zones. Correlation between biomass adjusted output of louse infestation and densities of farmed salmon in the production zones suggests that a large-scale density-dependent host-parasite effect is a major driver of louse infestation rates and parasite-induced mortality. The estimates are sensitive to many of the processes in the chain of events in the model. Nevertheless, we argue that the model is suited to assess spatial and temporal risks associated with farm-origin salmon lice.

1. Introduction

The Norwegian government recently produced a white paper on "Predictable and environmentally sustainable growth in Norwegian salmon and trout farming" (Anon, 2014 − 2015). A main goal for the government was to promote growth in the aquaculture industry by restricting regulations to focus primarily on environmental sustainability. The white paper suggested implementing a new system for regulating the volume of production of farmed salmonids by dividing the Norwegian coast into separate production zones. The production zones were constructed based on large-scale cluster analyses using hydrodynamic models to analyse water current connectivity between farms, aiming to minimize connectivity between zones (Ådlandsvik, 2015). Hence, the Norwegian coast was recently divided into 13 production zones for farming salmonids (Fig. 1), *i.e.* Atlantic salmon (*Salmo salar,* Salmonidae) and rainbow trout (*Onchorhyncus mykiss*, Onchorhyncus), in a separate regulation (Anon, 2017a). This new management system is referred to as "the traffic light system" (Vollset et al., 2017).

The white paper also presented a discussion on what indicators that should be subjects for evaluating future adjustments in the production capacity within production zones (Anon, 2014 − 2015). Only indicators of environmental concern and for which effects depend on the intensity of production, *i.e.* density-dependent environmental effects of production, were to be considered. In accordance with this premise, the government suggested that the salmon louse (*Lepeophtheirus salmonis*, Caligidae) for the time being should be the first and only indicator for evaluating future growth in the production capacity of the various production zones (Anon, 2014 − 2015). Sea lice control is recognised as a top priority subject in need of more insight to facilitate expansion of sustainable aquaculture also on a global scale (Jones et al., 2015). In the recently implemented Norwegian regulation, it is further specified

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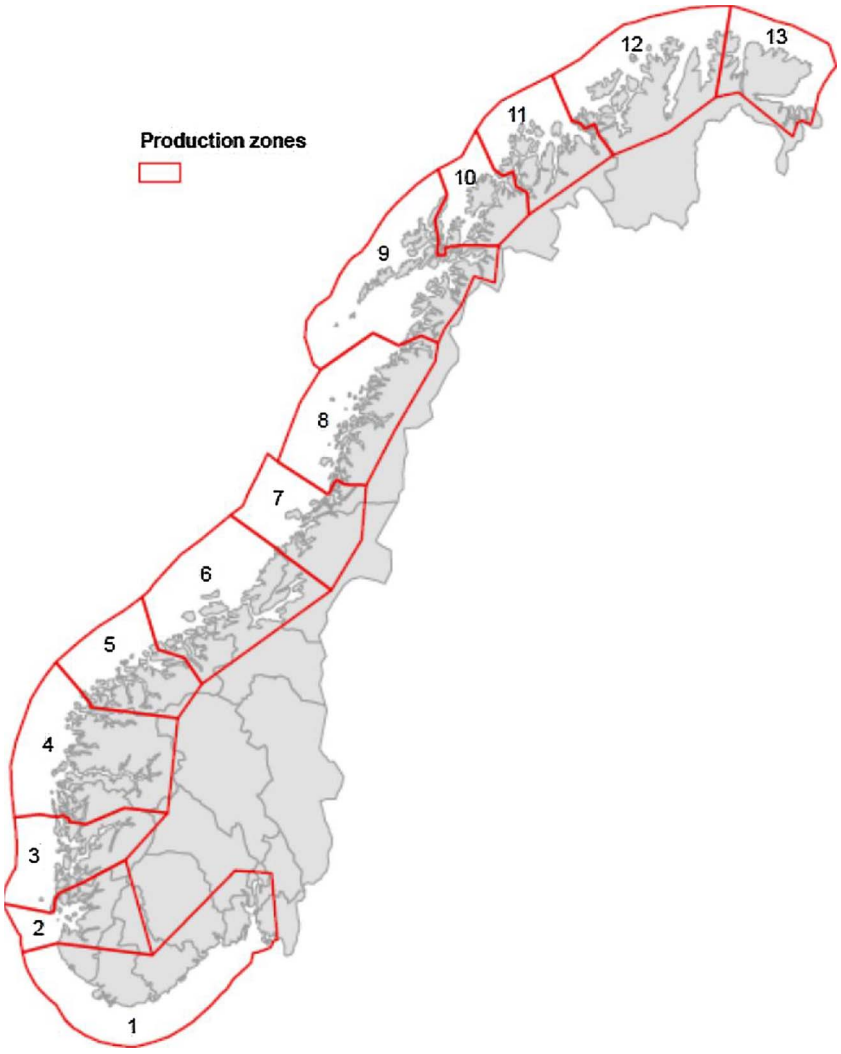

Fig. 1. Production zones 1–13 along the Norwegian coast.

that effects of salmon lice on wild salmonids should be the environmental indicator for the new management system and that the authorities are obligated to evaluate such effects every other year, in order to adjust the production volume within production zones (Anon, 2017a).

Norway holds more than 400 rivers producing Atlantic salmon (Hindar et al., 2011). The total abundance of wild Atlantic salmon, however, has declined over the last decades, both in terms of the number of populations and the productivity in freshwater and marine environments (Chaput 2012; Windsor et al., 2012). The total annual return of Atlantic salmon spawners to Norwegian rivers was recently estimated to about 522 thousand fish in 2015, which represents an estimated decline of 55% in returning salmon from around 1985 (Anon, 2016). At the same time, salmon farming in Norway has increased massively. The total sale of Atlantic salmon was estimated to be 1.30 million metric tonnes round weight in 2015, with an additional sale of 72.9 thousand tonnes of rainbow trout. Comparable figures in 1994 were 0.2 million metric tonnes of Atlantic salmon and 14.5 thousand tonnes of rainbow trout (Fiskeridirektoratet, 2017a). The present day production implies a standing stock of about 350–450 million farmed Atlantic salmon in marine farms along the Norwegian coast at all times (Fig. 2).

Effects of aquaculture on pathogen transmission to wild stocks of fish have received a lot of focus in different salmon-producing areas around the world (Johansen et al., 2011; Marra, 2005; Naylor et al., 2009). Discussions regarding effects of spill over of salmon lice from farms to wild salmonids have been especially controversial (Krkosek et al., 2007; Krkosek et al., 2006; Marty et al., 2010; Shepard et al., 2016). In Norway, effects of the massive numbers of farmed compared to wild salmon has been of special concern (Glover et al., 2017; Heuch and Mo 2001; Taranger et al., 2015; Torrissen et al., 2013). In a recent review of the major threats to Atlantic salmon in Norway, escaped farmed salmon was classified as the highest ranked threat, followed by the salmon louse (Forseth et al., 2017). The political dilemma in this situation is to balance the interests of a prospering salmon farming industry, while also ensuring the conservation of a large number of wild Atlantic salmon populations along the Norwegian coast. Many of the salmon-producing rivers are locally of economic and cultural importance due to angling and many are also threatened by other anthropogenic impacts, *e.g.* hydropower regulation and habitat alterations (Forseth et al., 2017).

To facilitate political decision-making concerning regulation of the production capacity within production zones, we developed a model for quantitative risk assessment of salmon louse-induced mortality of seaward-migrating post-smolts of Atlantic salmon. Louse infestations and louse-induced mortality are modeled for 401 salmon-producing rivers with marine outlets within specific production zones (Forseth et al., 2017). The expected timeframe for seaward migration of smolts is estimated for each river. Migrating post-smolt salmon are assumed to follow the shortest path from the river outlets in marine environments to the high seas, at a constant progression rate. During this seaward migration, salmon are exposed to salmon lice infestations. Louse infestation rates are modeled using a spatio-temporal model for louse