Environmental problems and regulation in the Aquaculture industry. Insights from Norway

Jon Olaf Olaussen

NTNU Business School, Norwegian University of Science and Technology

Abstract:

Since the beginnings of the aquaculture industry in Norway, the salmon farming industry has grown from a pioneering niche to a massive industrial adventure. Since 1992, Norwegian salmon production has increased to ten times its 1992 level. By 2015, the Norwegian production constituted 53% of the world's production of Atlantic salmon. Therefore, it could be said that salmon farming is the most important industry in rural Norway today, with a yearly landing value of about 6.1 billion EUR. As the production has grown, along with the income, numerous environmental issues have arisen. The present paper gives an overview of these environmental problems and discusses potential solutions, as well as the need for a better and more holistic regulation of the industry. The experience from Norwegian salmon farming with respect to environmental issues and regulation may give important insights to both other salmon producing countries as well as producers of other fish species.

Key words: Salmon farming, Environmental problems, Regulation, Sea lice, Escapement

JEL Codes: Q13, Q18, Q25

Running head: Environmental problems in aquaculture

1. Introduction

Norway has been a world leader in farmed salmon since the production technique was pioneered in the late 1960s. Since then, Norwegian salmon production has risen steadily from 600 tons in 1974 to about 1 300 000 tons today (Asche and Bjørndal 2011, Statistics Norway 2017). Since the start of aquaculture production in Norway, the salmon farming industry has grown from a niche market to a massive industries adventure. Salmon farming is, arguably, one of the most important industries in rural Norway today, with a yearly landing value of about NOK 60 billion (6.5 billion EUR). Production methods have been improved and obstacles solved at a rapid speed. From the time when the first farmers decided to put net cages in the fjords to today's massive production facilities, the need for management and regulation of the industry has changed dramatically.

As with any industrial production, there are costs and benefits associated with farmed salmon production. About 6000 jobs are created in the industry, and the contribution to GDP of Norway is in the range from 0,5-1% yearly (Statistics Norway 2017). Salmon production has ten doubled since 1992, and doubled since 2005. In 2015, Norwegian salmon production constituted 53% of the world's production of Atlantic salmon, while the Chilean production was 25% of the world market. As production has grown, along with the profits gained, the environmental impact has also increased in turn.

The salmon production industry not only affects the wild salmon populations, but also the sea trout populations, the coastal fisheries (especially shrimps and coastal cod), and the sea floor, due to environmental, noise, and visual pollution. The problem that has received the most attention is that of maintaining wild salmon stock, which spawns in the salmon streams of Norway. Currently, Norway has more than 400 watercourses with Atlantic salmon populations and holds about 25% of the world's healthy populations (Hindar et al., 2011). Consequently, Norwegian authorities have taken a particular responsibility to protect the species and its populations. According to the scientific board of salmon management, the two most severe challenges for this species is the escapement from fish farms and the high sea lice densities (Anon 2017a, Forseth et al. 2017).

The escapement from fish farms has always been a challenge, causing both direct economic losses to the sea farmers, as well as cross-spawning and hybrid (farmed and wild) salmon populations. Sea lice are parasites that attach to the skin of the salmon. Under natural conditions, this parasite is not a major problem for the wild salmon, but due to the enormous amount of hosts in the fjords year round (the farmed salmon), the number of sea lice in the fjords has proliferated. First and foremost, this is a problem for the wild smolt (young salmon) when they leave their river and migrate offshore to grow. On this migration route, they have to pass the fish farms and high lice density areas in the fjords. It has been found that if more than 10 lice attach to the skin of the young fish, they may die (Heuch et al. 2003). In addition, it turns out it may be an even bigger problem for the sea trout populations due to their longer sea journey (sometimes they stay in the fjord all year).

Pollution from aquaculture production takes many forms. One of the problems is that the high density of fish in small cages produces a lot of excrement and undigested feed. A carpet of sludge may cover the bottom floor, both beneath and around the aquaculture facilities. Another pollution problem is associated with sea lice. In order to keep sea lice numbers low in the farms, the industry has used several kinds of chemical treatments over the years. While the treatments target the sea lice in the farm, it may also be a problem for shrimps and other crustaceans in the surroundings of the farms. Unfortunately, sea lice can develop resistance to the chemicals, while wild crustaceans likely remain vulnerable.

2. Regulation

In the late 60s, farmers started experimenting with feeding salmon in sea cages. The activity was supported by the government as a means of adding to the income among small-scale farmers. Regulation was poor at this time as the activity was not considered especially important. In fact, in these early years of aquaculture production, escapements from fish farms were common, and the farmers received insurance money in association with such accidents. In 1973, the first law on concessions in salmon aquaculture was issued, and permission was needed to start sea farms (Aarset and Jakobsen 2009). In 1985, the first aquaculture law was issued. Unfortunately, this law failed to require concessions for hatchery production of smolt, and this resulted in an overinvestment in this sector. This overproduction resulted in a four-year period, where the salmon prices went down to half the previous level. In 1991, while as the industry faced allegations of dumping in the US market, the concession law was changed to allow one owner to have several concessions. This changed the structure in the sector dramatically, and small-scale farmers were replaced by fewer and bigger companies. In 2005, a new aquaculture law was issued. This time, the focus shifted towards sustainable production and growth in the sector (Norges Sjømatråd 2016). As of 2013, among the regulations a salmon farm must follow is the total number of salmon allowed per cage, which is restricted to 200,000 salmon. In addition, they have to remain under the total allowed biomass per concession, which is 780 tons (945 tons in the northernmost counties Troms and Finnmark). Moreover, to control the sea lice problem, they have to count the number of lice per salmon on a regular basis and take action if the number of adult female sea lice per fish is above 0,2 on average in week 16-22 (the migration period for wild smolts) (Anon 2017b). The limit is less than 0.5 in remaining season (Anon 2017b). This rule is now under change as the new traffic light system, issued in October 2017, puts aside this requirement, instead focusing on the presumed effect on the wild salmon mortality (see below).

3. Challenges with salmon production

3.1 Escapement

Since the very beginning of the salmon farming industry, salmon have unintentionally escaped from net pens that are damaged by storms, seals, and otters, or by daily wear and tear. The number of accidental escapes decreased in the mid-1990s because of safety investments in the sea ranches. Nevertheless, approximately 200,000 salmon still escape yearly from fish farms in Norway (Figure 1), which equals approximately half of the average total wild adult returns (Anon. 2017a). The yearly escapement numbers are uncertain, but according to the official statistics, farmed salmon escapes constitutes around half of the total yearly in-run of wild Atlantic salmon to Norwegian rivers. In addition, a recent meta-analysis of catch statistics and tagging studies has estimated that the actual numbers of escapees in Norway were 2–4 times higher than the numbers reported by the farmers during the period spanning 2005 to 2011 (Skilbrei et al. 2015).

In Norway, the wild Atlantic salmon stock is traditionally harvested in two different fisheries during its spawning run. First, the commercial and subsistence marine fishery catches a share of the marine returns in fishnets in the fjords and inlets. The remaining stock then enters the rivers and is exploited by a recreational fishery. According to the catch reports from 2013-2017, about 43% of the total catch is caught in the marine fishery, while the rest is caught in the rivers (Statistics Norway 2018a,b). When the fishing season in the river closes, the remaining fish spawns.

The farmed escapees interact with the native species in various ways. Ecologically, they may interact through competition, predation, hybridization, colonization, and spreading diseases and parasites (Forseth et al. 2017). Escaped farmed salmon may hence have a number of effects on the natural growth and economic value of wild salmon. The most important effects are the spread of diseases and the mixing of genes through interbreeding (introgession), which affect the reproduction rate (Glover et al. 2017, McGinnity et al. 2003, Fleming et al. 2000). Farmed salmon digs in the natives' spawning gravel, and their offspring are more aggressive and risk prone. Once farmed escapees survive and strive in the environment where native individuals reside, they become a part of the ecosystem and directly and indirectly interact with native individuals. For instance, farmed salmon can escape to the rivers, where they compete with native salmon. This competition over the natural habitat and food sources, as well as mates, may result in changes in the structure and productivity of the native stock (Fjørtoft et al. 2017). In the case of escaped farmed salmon, it is reported that successful inbreeding between escaped farmed and native salmon reduces the fitness and productivity (McGinnity et al. 2003), dilutes the genetic gene pools (Fjørtoft et al. 2017; McGinnity et al. 2004; Roberge et al. 2008), and threatens the survival of the native salmon offspring (Hindar et al. 2006). Karlsson et al. (2016) found statistically significant introgression in half of the wild populations studied and levels of introgression above 10% in 27 of 109 rivers represented by adult samples.

In addition, escaped farmed salmon can increase the sea lice density (Grimnes et al. 1996). Also, escaped farmed salmon may spread diseases and parasites, thus leading to the augmented mortality of native salmon (Bjørn and Finstad 2002; Gargan et al. 2002; Krkošek et al. 2006). If the number of escapees is low, the effects may be negligible, but the effects become severe as the number of escapees gets larger. In particular, some vulnerable native stocks may potentially go extinct with repeated invasion.

However, escaped farmed salmon may also be regarded as having positive effects. Farmed salmon can potentially increase the salmon stock available for both marine and recreational catches, *ceteris paribus*, and thus improve the profitability of these fisheries (Olaussen and Skonhoft 2008). As reported in Figure 1, escaped farmed salmon constitute a substantial part of the stock. This is not to say that invasion is no problem for the society as a whole, but it may reveal economic forces inducing a lack of incentives for different agents to control the invasion. In a sense, the large number of escaped farmed fish, which may constitute as much as 50% of the yearly catch of salmon in the sea fishing sector, may also hide the problem of a decreasing wild stock. Hence, escaped farmed species may generate economic impacts through markets. If invasive fish have a similar economic value as native wild fish, escaped farmed fish may increase the total stock level for harvesting.

Escaped farmed salmon (both Pacific and Atlantic salmon) is of great concern in a number of countries with fish farming industry, for example, United Kingdom, Scotland, Ireland, Iceland, Chile, USA, and Canada. In addition, the increasing farming of other fish species, such as cod, halibut, clams, and crabs, highlights the importance of addressing this issue. The bioeconomics of the interrelation between aquaculture and fisheries is studied by Anderson (1986), Ye and Beddington

(1996), Hannesson (2003), Olaussen and Skonhoft (2008), Liu et al. (2011), and Liu et al. (2012) while market interactions have been studied by Anderson (1985), Anderson and Wilen (1986), and Asche et al. (2005). Olaussen and Liu (2011) have studied the economic effects in terms of anglers reduced willingness to pay when the river catch consists of a large share of escaped farmed salmon.

Figure 1 about here

3.2 Sea lice

The collective term “sea lice” normally refers to a number of copepod crustaceans of the family *Caligidae* (Revie et al. 2009). Sea lice are external parasites that live on the skin of marine and anadromous species. The most common and extensively studied species is the *Lepeophtheirus salmonis,* which is a parasite specific to the salmonid species. This parasite is a problem in both the Atlantic and Pacific Oceans, while the Chilean farming industry 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 farm areas before they reach their offshore winter habitat. A recent study ranks the high sea lice densities, together with escaped farmed salmon from aquaculture, as the two most significant and expanding threats to the wild salmon populations in Norway (Forseth et al. 2017). Salmon aquaculture increases the sea lice density in the fjords and along the coast because they amplify the number of hosts for the lice by a magnitude of 100 (Heuch et al. 2005). Smolt infected by less than 10 sea lice are affected but typically survive whereas smolt with more than 10 lice have high mortality (Thorstad and Finstad 2018; Heuch et al. 2005; Holst et al. 2003). In some cases, close examinations of the infected fish have revealed up to 100 sea lice per fish, which cause certain death (Revie et al. 2009). It is not possible to give an accurate estimate regarding how much the smolt survival is reduced due to sea lice-induced mortality on a national scale. The effect varies between fjords, and from river to river. Recent results suggest an extensive exchange of lice between farmed and wild hosts, indicating that in farming-dense regions in Norway, aquaculture represents a major driver of salmon louse population structure (Fjørtoft et al. (2017). Furthermore, the annual loss of wild salmon to Norwegian rivers due to salmon lice was estimated at 50 000 adult salmon for the years 2010-2014. This corresponds to an annual loss of about 10% on a national level (Anon. 2017). As indicated, other salmon stocks, such as Pacific salmon, are also threatened by sea lice infections, and Krkosek et al. (2007) found a lice-induced mortality for pink salmon commonly exceeding 80%. Increased sea lice densities may be considered a type of biological pollution, and thus, a unidirectional externality running from the farmed salmon sector to the wild salmon sector.

3.2.1 Treatment

In order to cope with the increasing sea lice problems, chemical and mechanical treatments have been tried, as can be seen in Figure 2. The problem with chemicals is that the sea lice seems to be very adaptable. It can take a few years for evidence of resistance to appear following a new treatment with a new chemical. One solution has been to switch between different treatment methods, but the problem of resistance seems to be hard to overcome, and multi-resistance has emerged. In recent years, freshwater treatment has also become part of the toolbox, and the fear may be that the sea lice develops more tolerance for freshwater as well. If this happens, the problem in the rivers for the wild salmon population may be serious, because today they are, in some sense, protected by the fact that the sea lice cannot handle freshwater. Another problem that has recently been highlighted by coastal shrimp fishermen and others, is that the chemical treatments may also affect coastal shrimp and other crustaceans populations, as well as fish. As Samuelsen et al. (2015, p. 115) states, "During medication, most wild fauna contained teflubenzuron residues, and polychaetes and saith had highest concentrations. Eight months later, only polychaetes and some crustaceans contained drug residues. What dosages that induce mortality in various crustaceans following short or long-term exposure is not known, but the results indicate that the concentrations in defined individuals of king crab, shrimp, squat lobster, and Norway lobster were high enough shortly after medication to induce mortality if moulting was imminent". Fortunately, it can also be argued that as the sea lice becomes resistant to a new chemical treatment, it will make no sense to continue using it, and this may in turn reduce the threat to crustaceans in general.

The treatment of the sea lice problems also involves costs to the industry. Abolofia et al (2017) estimated that the cost of sea lice treatment constituted production costs ranging from 0.12 to 0.67 US$/kg, or in the range of 2.27 to 13.10% of yearly revenues. In addition, the increase in "other production costs", where sea lice treatment constitutes 80% of the costs, is the main driver of increased production costs, increasing from an average of 0.36 US$ per kg on average in 2008 to 0.78 US$ per kg in 2015 (Fiskeridirektoratet 2017).

On the positive side, the use of antibiotics in the aquaculture industry in Norway is very low (see Figure 3). In 1987, the use of antibiotics was 887 milligram per kg fish produced, while it was down to

0.20 milligram in 2015 (Anon. 2016). In Chile, on the other hand, the use was still 660 milligrams per kg produced fish (Jensen 2017).

Figure 2 and 3 about here

3.3 Fish welfare

The question of fish welfare is closely related to the topics of sea lice treatment and fighting off diseases. In 2016, 19% of the salmon died in the sea-cage stage (Hjeltnes et al. 2017), corresponding to 53 million fish. In a study focusing on the cause of death in the sea cage stage, poor smolt quality and infections were pointed out as being the two most significant causes, while the other three categories were mechanical injury, environmental causes, and miscellaneous (Bleie and Skrudland 2014). Sea lice infections lead to death, either through infections in the skin from wounds, or due to chemical and/or mechanical treatment (Hjeltnes et al. 2017). In addition, the high densities of hosts leads to challenges with respect to other diseases, such as Pancreas disease (PD) and infectious salmon anemia (ISA) (Bleie and Skrudland 2014).

Another aspect of fish welfare is associated with one of the sea lice fighting strategies. By using cleaning fish, that is, fish species that feed on sea lice, the aquaculture industry has tried to reduce the treatment with chemicals. The cleaning fish species are labrid fish (mostly ballan wrasse, *Labrus bergylta*, and goldsinny wrasse, *Ctenolabrus rupestris*), and lumpfish *Cyclopterus lumpus* (Powell et al. 2017). It turns out the mortality rate of these species is very high at an average of 33% after only 6 months in the sea. For the lumpfish, the mortality rate was 48% after 6 months (Nilsen et al. 2014). This indicates that the ethics of the use of cleaner fish is an issue, with very little debate thus far. This is quite surprising, given that fish welfare in aquaculture is explicitly regulated by law, which stipulates that the operation must be satisfactory with respect to health and welfare (Lovdata 2008).

3.4 Pollution

As with all industrial production, the aquaculture industry brings a level of pollution along with it. We have already mentioned sea lice treatment chemicals. In addition, the aquaculture industry constitutes a major part of the release of nutrition to Norwegian fjords. This is mainly due to releases from feed and fish faeces. Due to the present high level of production, the release of nutrition from the sector is at the same level as the sewage from about 10 million people, or about twice the Norwegian population. Interestingly, while there is a focus on release from land-based industry, this issue has been more or less ignored in the fjords. The result is seen in Figures 4 and 5, where the release of phosphorus from the aquaculture industry is about 45 times higher than the total from the rest of the Norwegian industry, and about 9 times as high as the natural drainage. In addition, the release of nitrogen from aquaculture production is about 24 times the release from the remaining industry and is almost as high as the natural drainage (0.7 times natural drainage).

Figure 4 and 5 about here

4. New regulation, traffic light system

Sea lice infection on salmon farms has been regulated since 1997 to reduce the harmful effects of lice on farmed and wild fish (Heuch et al. 2005). Regulations set thresholds for the maximum mean number of sea lice per fish and a compulsory reporting system for all mobile stages of infective lice. From 2000 to 2013, the legal lice infection thresholds were set to 0.5 adult female lice per fish, or 3 lice per fish of other mobile stages (i.e., adult males or pre-adult mobiles) during the period spanning Jan 1–Aug 31, and 1 adult female or 5 other mobiles per fish across the period between Sep 1–Dec 31. From 2013, the limits for taking action have been 0,2 lice per salmon on average in week 16-22 (the wild smolt migration period), and less than 0.5 lice per salmon in remaining season (Anon 2017b). This threshold is enforced by the Norwegian Food Safety Authority (NFSA). If thresholds are exceeded, it is mandatory for the farmer to treat or slaughter their fish within two weeks. The NFSA requires farmers to regularly count sea lice in their pens and report the highest mean count during a month.[1] Before August 2009, farmers were mandated to report the highest mean counts of sea lice from a 20-fish sample from a single net pen. After this date, farmers were required to report the means from samples of 10 fish from 50% of all active pens. In addition, all pens are to be counted for every two rounds of sampling in order to improve control (Abolofia et al. 2017).

[1] If the sea temperature is above 4°c, the counts must be performed on a weekly basis, otherwise every 14th day (Anon.2013).

The government of Norway has decided to introduce a new system for growth in the aquaculture sector, labelling it as a traffic light system. The idea is that the key to growth is the sea lice pressure. This means that the sea lice effect on wild salmon mortality will be the indicator with respect to production growth. In areas where sea lice cause wild salmon smolt mortality less than 10%, a green light for increasing production by 6% will be given. A yellow light will be given in the case where sea lice induced mortality is between 10 and 30%. A yellow light means that the growth is on hold, i.e., constant production. If an area gets a red light, the sea lice induced mortality is higher than 30%, and production should be reduced. However, this reduction will not take place before the next evaluation period.

There are several problems with this system. First, basing potential growth on only one indicator is a rather strange idea (see Figure 6). As mentioned above, and as the figure indicates, there are several other factors, and one of them, escapement from fish farms, is considered equally important for the protection of the wild salmon stock. One reason why escapement is not yet included may be the poor correlation between the size of the farming industry in an area and the occurrence of farmed fish in the rivers. This is because escaped farmed salmon migrate over long distances and do not necessary return to spawn in rivers near where they escaped. This asymmetry between escapement location and damage location may point in the direction of adding escapement as an indicator on the national, not regional level.

In addition, as mentioned above, measures to fight sea lice may introduce new challenges, such as the effect of chemicals on shrimps, other crustaceans, and local fish populations (see Figure 6). Second, in the former regime, there is a rule associated with the number of sea lice per fish, that is, an objective criteria. The new criteria is more open for discussion, as someone will have to estimate how different sea lice densities affect the mortality of wild salmon, which is a challenging task. To be fair, there is a large group of scientists within a well-organized system that do the assessment of infestation and mortality risk and make these recommendations, but probability considerations are always open for debate. Third, as the focus is only on one challenge, the incentives to invest in technologies that mitigate other problems, such as escapement, will probably be less, as the focus will shift towards sea lice treatment.

Figure 6 about here

Fourth, there is a fish welfare perspective that is completely neglected. The aquaculture sector is a sector where 19% of the fish (2016) die in the nets before they reach the market size (Fiskehelserapport 2016).

Overall, and to sum up, there seems to be many reasons why one should reconsider the narrow indicator system introduced through the traffic light system. When the system and problem is complex, and negative externalities multidimensional, regulating without a holistic perspective may be directly damaging. On the other hand, sea lice is no doubt a severe challenge, and it may be argued that the system, at least in part can give an incentive to develop new and less damaging ways of production, since growth may be limited in areas with high infection pressure. Also, it should be mentioned that Norwegian authorities in parallel has introduced systems for “green concession” and “technology developing concessions”. While some of these concessions are issued mainly to initiatives addressing the sea lice problem, there are also other that aim for more holistic solutions, such as land-based and closed containment production systems.

5. Discussion and concluding remarks

The main problem with the previous and current regulation in light of environmental concerns seems to be that there are too weak incentives to shift towards new and less damaging ways of production. One of the most promising solutions would be the development of closed containment production systems for salmon aquaculture, that is, a transmission from the open net cages to more closed containment facilities. Small-scale aquaculture production is already available, and projects of a commercial scale have also been conducted in Canada and Denmark. Investing in such technologies will be costly in the short run for the aquaculture sector, but may turn out beneficial in the long run; in any case, this technology has the potential to solve many of the challenges between the wild and farmed salmon. Since closed containment systems separate farmed fish from wild fish and the environment, it will alleviate or eliminate most of the problems caused by open cage farming, such as escapees, spread of diseases, and sea lice. As a result, the impact of farming on the wild salmon would be considerably reduced.

The underlying institutional challenge in the regulation of the aquaculture sector is that aquaculture is managed by the Ministry of Trade, Industry, and Fisheries in Norway, while the wild salmon is under the management of another department, the Ministry of Climate and Environment (Liu et al.

2011). This problem was highlighted already in the first year of the traffic light system, as the Ministry of Trade, Industry and Fisheries acknowledged the advice for yellow light from the scientific committee in one of the counties, that is a hold signal. However, he executed his right to let other matters count, and as a result the county were given a green light and the possibility to grow with 6%. It may seem unfortunate that the Ministry of Climate and Environment is not part of this decision process, as this could spell weak support from the government regarding wild salmon interests.

The present paper has highlighted environmental concerns in the Norwegian salmon aquaculture production. The problems are transferable to other aquaculture producing countries as well as producers of other fish species, and many of these challenges are shared with Chilean and North American producers. Hopefully, the apparent problems due to rapid growth experienced in the Norwegian region may prevent and help other potential international producers to manage their aquaculture production in a sustainable way, whether in salmon farming or other production.

References:

Aarseth, B., & Jakobsen, S-E. (2009). Political regulation and radical institutional change: The case of aquaculture in Norway. *Marine Policy* 33, 280-287.

Abolofia, J., Asche, F., & Wilen J.E. (2017). The Cost of Lice: Quantifying the Impacts of Parasitic Sea Lice on Farmed Salmon. *Marine Resource Economics* 32(3), 329-348

Anon. (2013). Bransjeveileder lakselus, lusedata.no, http://lusedata.no/for-naeringen/veileder-for-telling-av-lakselus/

Anon. (2014). Status for norske laksebestander i 2014. Rapport fra Vitenskapelig råd for lakseforvaltning no 6, 225 p.

Anon. (2017a). Status for norske laksebestander i 2017. Rapport fra Vitenskapelig råd for lakseforvaltning no 10, 152 p.

Anon. (2017b). Forskrift om bekjempelse av lakselus i akvakulturanlegg. Lovdata. https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140

Anon. (2016). Usage of Antimicrobial agents and occurrence of Antimicrobial resistance in Norway. NORM-VET (2016). Tromsø/Oslo.

Anderson, J.L. (1985). Market Interactions between Aquaculture and the Common-Property Commercial Fishery. *Marine Resource Economics* 2(1), 1–24.

Anderson, J.L., & Wilen, J.E. (1986). Implications of Private Salmon Aquaculture on Prices, Production, and Management of Salmon Resources. *American Journal of Agricultural Economics* 68, 866–79

Asche, F., & Bjørndal, T. (1990) *The Economics of Salmon Aquaculture*, Wiley-Blackwell.

Asche, F., Guttormsen, A.G., Sebulonsen, T. & Sissener, E.H. (2005). Competition between farmed and wild salmon: the Japanese salmon market. *Agricultural Economics* 33, 333–340.

Bjorn, P.A. & Finstad, B. (2002). Salmon lice, Lepeophtheirus salmonis (Kroyer), infestation in sympatric populations of arctic char, Salvelinus alpinus (L.), and sea trout, Salmo trutta (L.), in areas near and distant from salmon farms. *ICES Journal of Marine Science*, 59, 131–139.

Bleie, H., & Skrudland, A. (2014). Tap av laksefisk i sjø. *Rapport fra Matilsynet.*

Fiskeridirektoratet (2017). Rømmingsstatistikk. www.fiskeridir.no/Akvakultur/Statistikk-akvakultur/Roemmingsstatistikk

Fjørtoft, H.B., Besnier F., Stene, A., Nilsen F., Bjørn, P. A., Tveten, A., Finstad, B., Aspehaug, V., & Glover, K.A. (2017). The Phe362Tyr mutation conveying resistance to organophosphates occurs at high frequencies in salmon lice collected from wild salmon and trout. *Scientific Reports,* available online 10.27.2017.

Fleming, I.A., Hindar, K., Mjølnerud, I.B., Johnsson, B., Balstad, T., & Lamberg, A. (2000). Lifetime Success and Interactions of Farm Salmon Invading A Native Population, *Proc. R. Soc. Lond. B.* **267**, 1517–1523.

Folkehelseinstituttet (2017). Statistikk. Legemidler i fiskeoppdrett 2016. www.fhi.no/hn/legemiddelbruk/fisk/2016-salg-av-lakselusmidler-er-synkende/

Forseth, T., Barlaup, B.T., Finstad, B., Fiske, P., Gjøsæter, H., Falkegård, M., Hindar, K., Mo, T.A., Rikardsen, A.H., Thorstad, E.B., Vøllestad, A. & Wennevik, V. (2017). The major threats to Atlantic salmon in Norway. *ICES Journal of Marine Science* 74, 1496-1513.

Gargan, P.G., Tully, O., & Poole, W.R. (2002). The relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992–2001. In D. Mills (Ed.), Salmon on the Edge (pp. 119–135). Blackwell Science Ltd, Oxford, UK.

Glover, K. A., Solberg, M. F., McGinnity, P., Hindar, K., Verspoor, E., Coulson, M. W., Hansen, M. M., Skaala, Ø., & Svåsand, T. (2017). Half a century of genetic interaction between farmed and wild Atlantic salmon: Status of knowledge and unanswered questions. *Fish and Fisheries*, 1-38

Grimnes, A., Birkeland, K., Jakobsen, P.J., & Finstad, B. (1996). *Lakselus-Nasjonal og Internasjonal Kunnskapsstatus*, NINA fagrapport 18.

Hannesson,R. (2003). Aquaculture and Fisheries. *Mar. Pol*. **27**, 169–178.

Heuch, P. A., Revie, C. W., & Gettinby, G. (2003). A comparison of epidemiological patterns of salmon lice, Lepeophtheirus salmonis, infections on farmed Atlantic salmon, Salmo salar L., in Norway and Scotland. *Journal of Fish Diseases*, 26, 539-551

Heuch, P.A., Bjørn, P.A., Finstad, B., Holst, J.C., Asplin, L., & Nilsen, F. (2005). A review of the Norwegian 'National Action Plan Against Salmon Lice on Salmonids. *Aquaculture* 246, 79-92

Hindar, K., Fleming, I. A., McGinnity, P., & Diserud, O. (2006). Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES Journal of Marine Science, 63*, 1234-1247.

Hindar, K., Hutchings, J. A., Diserud, O. H., & Fiske, P. (2011). Stock, recruitment and exploitation. In Atlantic Salmon Ecology, pp. 299–332. Ed. by Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal. Wiley-Blackwell, Oxford, UK

Hjeltnes, B., Bornø, G., Jansen, M.D., Haukaas, A., & Walde C. (eds). (2017). The Health situation in Norwegian Aquaculture 2016. Norwegian Veterinary Institute, Oslo.

Jensen, P.M. (2017). Høyeste antibiotikabruk i Chile på 9 år. Kyst.no. https://kyst.no/nyheter/hoyeste-antibiotikabruk-i-chile-pa-9-ar/

Karlsson, S., Diserud, O. H., Fiske, P., & Hindar, K. (2016). Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations. Ices Journal of Marine Science, 73, 2488–2498.

Krkošek, M., Lewis, M.A., Morton, A., Frazer, L.N., & Volpe, J.P. (2006). Epizootics of native fish induced by farm fish. *Proceedings of the National Academy of Sciences of the USA*, 103(42), 15506–15510.

Liu, Y., Diserud, O.H., Hindar, K., & Skonhoft, A. (2012). An ecological-economic model on the effects of interactions between escaped farmed and wild salmon. *Fish and Fisheries*, 14(2), 158–173.

Liu, Y., Olaussen, J.O, & Skonhoft, A. (2011). Wild and farmed salmon in Norway. A review. *Marine Policy* 35, 413-418

Lovdata (2008). Forskrift om drift av akvakulturanlegg (akvakulturforskriften), §5.

https://lovdata.no/dokument/SF/forskrift/2008-06-17-822

McGinnity, P., Prodöhl, P., Ferguson, A., Hynes, R., Maoile´idigh, N.O., Baker, N., Cotter, D., O'Hea, B., Cooke, D., Rogan, G., Taggart, J., & Cross, T. (2003). Fitness Reduction and Potential Extinction of Wild Populations of Atlantic Salmon, Salmo Salar, as a Result of Interactions with Escaped Farmed Salmon, *Proc. R. Soc. Lond. B*. **270**, 2443–2450.

McGinnity, P., Prodöhl, P., Maoile´idigh, N. O., Hynes, R., Cotter, D., Baker, N., O'Hea, B., & Ferguson, A. (2004). Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. *Journal of Fish Biology,* 65(1), 173–187.

Nilsen, A., Viljugrein, H., Røsæg, M.V., Colquhoun, D. (2014). Rensefiskehelse- kartlegging av dødelighet og dødelighetsårsaker. *Veterinærinstituttets rapportserie* 12-2014. Oslo: Veterinærinstituttet.

Norges Sjømatråd (2016). Laksefakta. https://laksefakta.no/

Norwegian Environment Agency (2017). Eutrophication. http://www.environment.no/topics/marine-and-coastal-waters/eutrophication/

Olaussen, J.O. & Liu, Y. (2011). On the willingness-to-pay for recreational fishing -Escaped farmed versus wild Atlantic salmon. *Aquaculture Economics & Management* 15(4), 245-261

Olaussen, J.O., & Skonhoft, A. (2008). On The Economics of Biological Invasion: An Application to Recreational Fishing," *Natural Resource Modeling* 21(4), 2008: 625-653.

Powell, A., Treasurer, J.W., Pooley, C.L., Keay, A.J., Lloyd, R., Imsland, A.K., de Lean, C.G. (2017). Use of lumpfish for sea-lice control in salmon farming: challenges and opportunities. *Reviews in Aquaculture,* doi:10.1111/raq.12194

Roberge, C., Normandeau, E., Einum, S., Guderley, H., & Bernatchez, L. (2008). Genetic consequences of interbreeding between farmed and native Atlantic Salmon: Insights from the transcriptome. *Molecular Ecology,* 17(1), 314–324.

Samuelsen O.B., Lunestad B.T., Hannisdal R., Bannister R., Olsen S., Tjensvoll T., Farestveit E., & Ervik A., (2015). Distribution and persistence of the anti sea-lice drug teflubenzuron in wild fauna and sediments around a salmon farm, following a standard treatment. *The science of the total environment 508: 115-121*

Skilbrei, O. T., Heino, M., & Svåsand, T. (2015). Using simulated escape events to assess the annual numbers and destinies of escaped farmed Atlantic salmon of different life stages, from farms sites in Norway. *Ices Journal of Marine Science*, 72, 670–685.

Statistics Norway (2017). Aquaculture. https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett

Statistics Norway (2018a). Elvefiske etter laks, sjøaure og sjørøye. https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiske-og-fangst

Statistics Norway (2018b). Sjøfiske. Fangst etter fiskeslag og vektklasse. https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiske-og-fangst

Thorstad, E.B., & Finstad, B. (2018). Impacts of salmon lice emanating from salmon farms on wild Atlantic salmon and sea trout. NIN Report 1449: 1-22.

Ye, Y., & Beddington, J.R. (1996). Bioeconomic interactions between the capture fishery and aquaculture. *Marine Resource Economics* 11(2), 105-123.

Figure caption list:

Figure 1. Yearly escape of salmon from fish farms and inflow of wild salmon to Norwegian rivers. Source: Fiskeridirektoratet (2017) and Anon (2017a).

Figure 2. Yearly use of sea lice treatment chemicals. Hydrogen peroxide (Black line) measured in tons (right axes). Source: Folkehelseinstituttet (2017).

Figure 3. Yearly use of drugs for the treatment of fish. Source: Folkehelseinstituttet (2017).

Figure 4. Phosphor disposal to fjords by source.

Source: Norwegian environment agency (2017)

Figure 5. Nitrogen disposal to fjords by source.

Source: Norwegian environment agency (2017)

Figure 6. A schematic overview of the interdependencies and externalities in aquaculture production

Figure 1

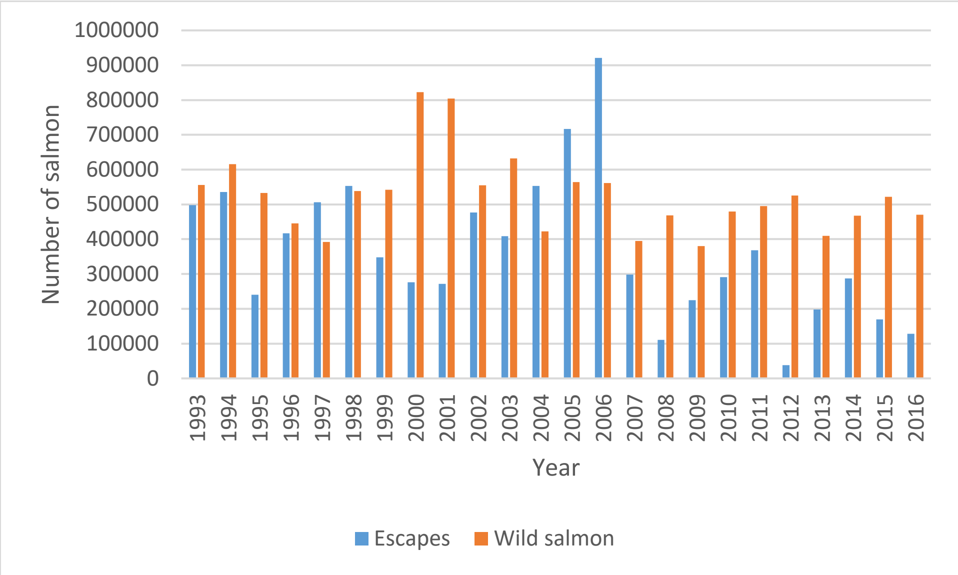


Figure 2:

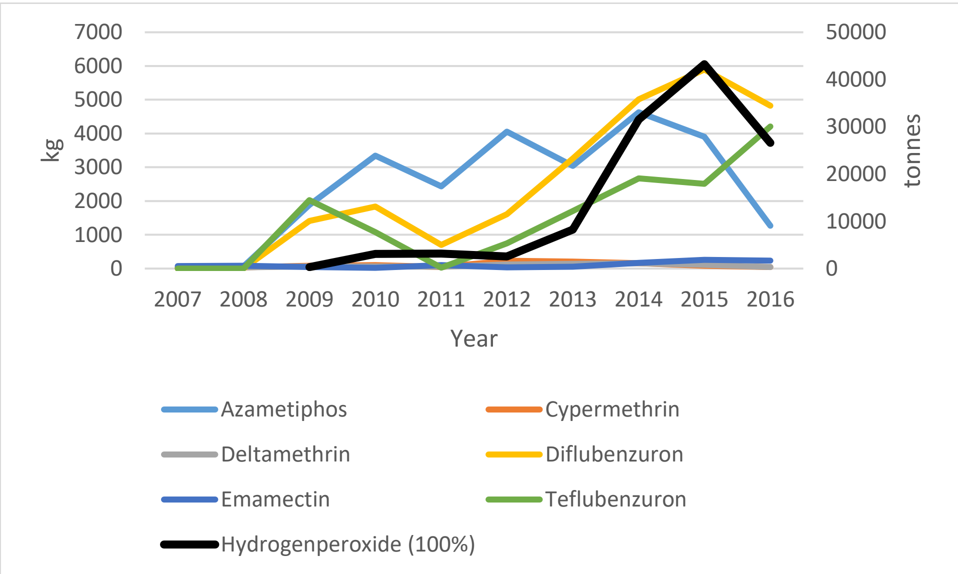


Figure 3

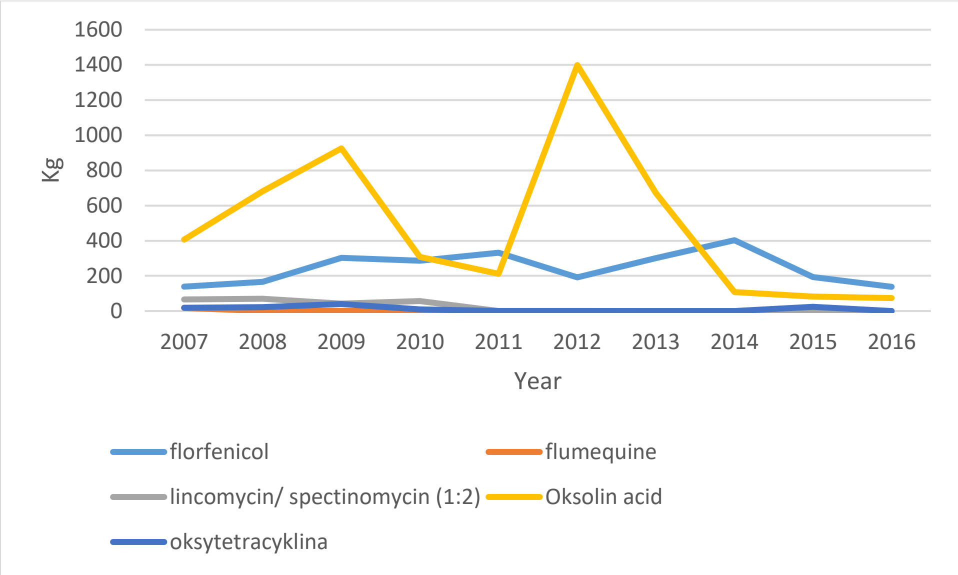
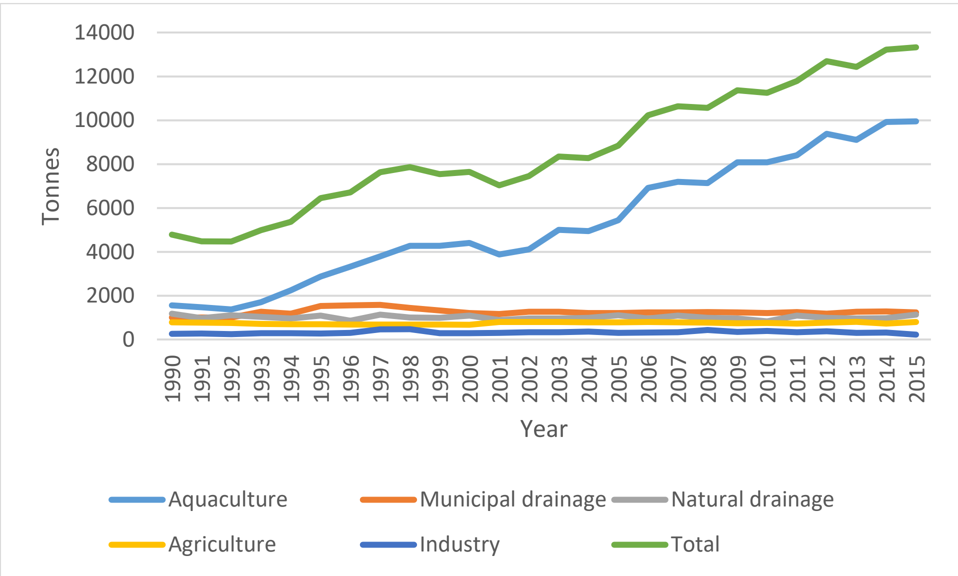


Figure 4



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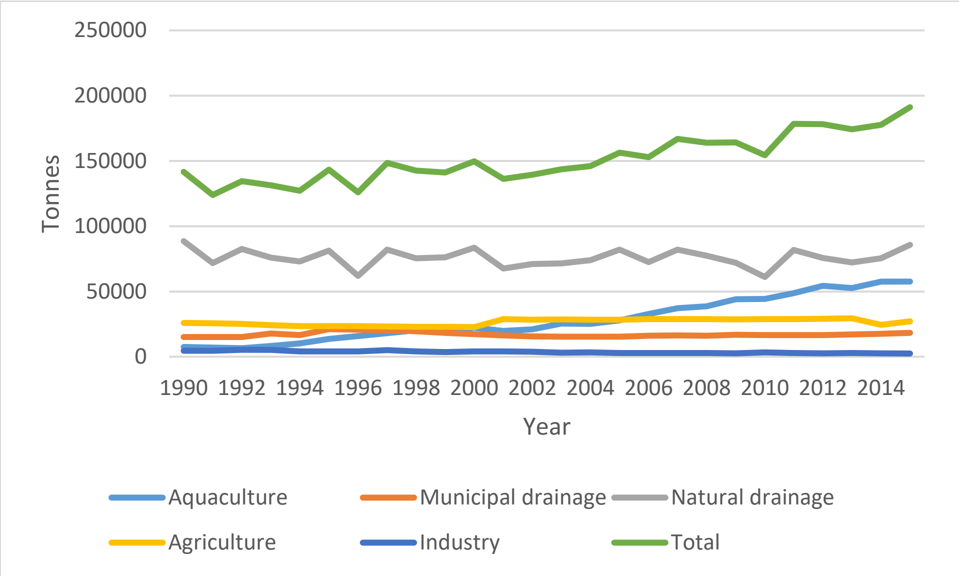
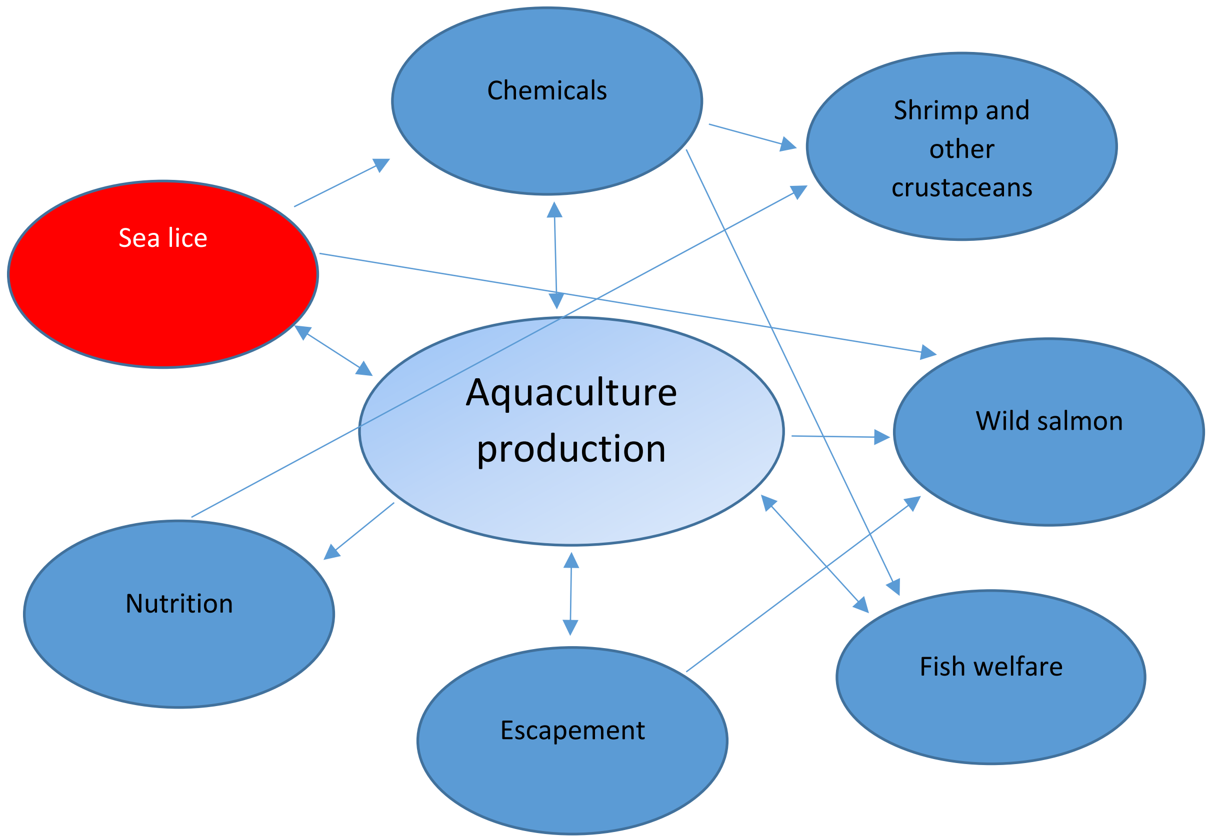


250000
200000
150000
100000
50000
0
Tonnes
1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014
Year
Aquaculture
Municipal drainage
Natural drainage
Agriculture
Industry
Total

Figure 6


Chemicals
Shrimp and other crustaceans
Sea lice
Aquaculture production
Wild salmon
Nutrition
Escapement
Fish welfare