

# The role of “green” licences in defining environmental controls in Norwegian salmon aquaculture.

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# Abstract

The study examines the problem of externalities in the Norwegian aquaculture sector.

The two main environmental challenges of Norwegian salmon aquaculture at the moment are the sea lice spread and farmed fish escape. Without dealing with these challenges, no increase in production was possible. At the same time the growth in the output is needed to satisfy the increasing demand for salmon products on the global market. The allocation of “green” aquaculture licences in 2013 was an attempt to find a compromise. New licences were sold to producers under the condition that they will use new technologies for effective prevention of sea lice infestation and escape incidents. In this thesis the role of “green” licences in designing environmental controls is discussed. These regulations are seen as an important experiment that provided new economic information that can be studied and used for new environmental policy. The theory of externalities and pollution control is applied to the problem of sea lice, which is studied as biological pollution. The damage and abatement cost of the sea lice pollution is studied in order to discuss possibilities of using direct and market-based control instruments. By a simple assessment of the costs of different abatement methods applied on “green” farms, it was demonstrated that the technological development plays an important role in forming the economy-wide marginal abatement cost function.

Key words: aquaculture, Atlantic salmon, green licences, pollution, externalities, damage of pollution, abatement cost, command-and control instruments, market-based instruments.

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# Chapter 1: Introduction

## 1.1 Environmental issues in Norwegian aquaculture

Norwegian salmon aquaculture is a relatively young industry that has experienced rapid growth since the early 1970s (Kolle, 2014).<sup>1</sup> The development was characterised by expanding in size and the number of fish farms, technological improvement and the high capitalisation of the sector. The total production value of the aquaculture industry in 2013 was over 40 billion NOK, 93.6% of which is salmon production, and 5.7% rainbow trout products (SSB, 2014). These two salmonids accounted for about 70% of Norwegian seafood export value in 2013.

The demand for salmon in the global market is rising by on average 13% a year, according to the Norwegian Seafood Council (Aandhal, 2014). In order to satisfy growing demand and retain Norway's position as the major exporter of salmon, production growth is required, but there are environmental issues that prevents Norwegian fish farming from expanding.

The production method used in salmon farming are quite similar among all producers. Most farms use open sea cages placed in fjords. Norwegian fjords, however, are vulnerable ecosystems and are the habitat of a variety of species including wild salmonids migrating from adjacent rivers. The industry thus has a negative impact on the environment in several ways. First, it has significant influence on the wild stock of salmon and trout due to the escape of cultured fish from sea cages. The proportion of farmed fish present in rivers all over Norway in recent years has been on average 12-13% (Fiske, 2013). It is believed that farmed fish affect the genetic pool of local stocks and can also destroy the spawning grounds of wild fish. The precise damage, though, has not yet been estimated.

Another major environmental problem associated with salmon farming is the spread of fish diseases that affects not only wild salmonids, but fish in neighbouring farms. Sea louse, which is a parasite commonly presented in the natural environment has become the most important problem for fish health in Norwegian aquaculture. Sea lice spread in large concentrations causes mortality in both wild and farmed fish either directly or by transferring secondary bacterial and viral diseases.

Norwegian authorities and scientists now pay much of their attention to these two challenges, but there are many other environmental issues that should be mentioned, such as the

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<sup>1</sup> Common names of species – salmon and trout – are used in the paper instead of scientific names: Atlantic salmon (*Salmo Solar*) and rainbow trout (*Oncorhynchus mykiss*) respectively.

organic waste from fish farms and chemical pollution as a result of disease treatments in sea cages. Due to time restrictions only one of the issues will be studied in this thesis. This study is thus focused entirely on the sea lice challenge, because the situation with lice spread is considered critical, and the urgent need for adequate measures is recognised by the Norwegian government (Ministry of Trade, Industry and Fisheries, 2014) . It should be stressed, however, that the methods applied in the thesis can also be applied to the problem of fish escape problem.

Regulations have become more strict as the industry expanded. Aquaculture in Norway is mainly regulated by the Directorate of Fisheries, but other sectorial authorities are involved in the control of veterinary and food safety matters, coastal planning, water management and issues of environmental health (Aquaculture Act, 2005).

Despite all the regulations, the development of salmon farming in Norway has now reached a point when environmental concerns have become a restrictive factor for further growth. The current rules have proved to be insufficient for dealing with the problem of sea lice and escapes. As a consequence, Norwegian authorities are facing the dilemma between the need for growth and the need for environment protection. It is important to point out the difference between this kind of controversy in aquaculture and other industries. Practically all industries are dealing with the same kind of trade-off between growth and environmental impact, but in aquaculture the pollution not only affects the environment but the industry itself, especially when it comes to sea lice infection. This makes the problem even more urgent.

The study looks at this dilemma as a background to investigating recent attempt of the Norwegian state to deal with it in the form of allocating “green” aquaculture licences. The research aims to examine the effects the regulations will have on the future management of the sector.

## **1.2 “Green” licences allocation**

According to the Aquaculture Act (2005), a licence is needed to run a fish farm. In salmon farming the allocations are made in rounds. Production growth, therefore, is only possible when new licences are issued. In 2013, three years after the previous allocation round, the government issued new aquaculture licences for salmon and trout in order to meet the growth objectives. Since environmental challenges, mainly sea lice and escapees had by that time become critical, participation was conditioned by the performance of farms in terms of prevention of those. Taking into account that technological innovations are essential for addressing this type of challenges, the main requirement for the applicants was the use of a new technology or production method with a



significant effect in terms of sea lice level reduction and/or reduction of the risk of harmful effects to wild stocks caused by fish escape (Forskrift om løyve til havbruk med matfisk, 2013).

There were 255 applications for 45 “green” licences, which demonstrates the demand and willingness of the fish farms owners to pay for the growth. The design of the regulations and the way they were implemented caused a huge public reaction. The allocation was made in three groups, with a closed auction principle in one, which was quite a controversial measure. A substantial number of applications were rejected purely due to formalities and as a consequence, there were many complaints. The working group that was responsible for the whole process was just as criticised as the criteria and the way applications were evaluated was questioned by the industry (Furuset, 2013).

The aspects of regulation design, however, are not the focus of this study. The “green” licences cannot be seen as a final solution to the dilemma described above for many reasons. First of all, the regulations cover only a small part of production while the rest of the industry still runs the farms in the same way as before. Secondly, the effect of the regulations is yet to be evaluated. “Green” licences can instead be viewed as an experiment in a situation of public pressure and the absence of ready solutions. The point of discussion in this thesis is that an experiment like that, which might not be very effective in itself, provides additional information and experience that is useful for designing environmental instruments for aquaculture in the future. This is primarily viable economic information, since the process revealed the market price of a licence, willingness to pay, innovation capacity of the firms, structure of the sector, etc. There is also important social information, as the public reaction can be analysed and the design of regulations can be improved.

This study is concerned with the economic information that can be obtained from the allocation results. The research problem is then formulated from the environmental economics perspective.

### **1.3 Research problem and research questions**

Pollution control theory principles are applied in the research. Sea lice are seen as a type of pollution that affects not only the environment, but also farmed fish health and therefore, the productivity of farms. The cost of the environmental damage is not fully internalized by the industry and then are externalities. The main concept in the externality problem is that of the social optimum, where the damage paid by society is being compensated for by the polluter in one way or another. The optimum level of pollution can be achieved by reduced production output, the use of alternative

inputs, or changed production technologies (Perman, Ma, Common, Maddison, & McGilvray, 2011). The latter is of particular importance in this thesis. The condition of achieving the socially optimal level of pollution can be formulated in different ways. One of the definitions is given in Perman et al. (2011, p.147): “The net benefits of pollution can be maximized only where the marginal benefits of pollution equal the marginal damage of pollution”.

It follows from the definition that in order to achieve the social optimum, the regulating authority must know the functions of marginal damage and marginal benefit. In this concept the damage is defined as the costs of pollution that are not met by producer. This can be also referred to as benefits that arise from reduced pollution damage. The benefits of pollution in the concept are the costs that a producer avoids when increasing emission levels. It means that by polluting the industry saves resources that would otherwise be spent as production loss, investment in alternative inputs or cleaner technologies. This is also referred to as abatement cost. In this study, the terms ‘damage’ and ‘abatement costs’ (total or marginal) will be used as definitions of the two functions.

The research problem from the economic perspective will then be formulated in the following way: “How does the “green” licences allocation improve knowledge of the damage and abatement cost functions, and how can this information be used when designing environmental instruments in Norwegian salmon aquaculture?”

It is assumed that these particular regulations results will generally give more information about the abatement costs than damage function. The hypothesis here is that after “green” licences, the technology will play the central role, and the choice of abatement technologies by the industry will form the aggregated abatement cost function. Emphasis will therefore be placed on this function. Available information about the damage function will also be discussed.

In order to examine the research problem, the following research questions should be addressed:

1. What are the estimations of damages, abatement costs and social optimum for sea lice pollution in the Norwegian aquaculture sector?
2. What instruments for achieving social optimum exist (and have been tried) in the industry?
3. How can “green” licences allocation results improve knowledge of the abatement cost function and how can it influence the future choice of control instruments?

Analytic and quantitative methods are used in this study. The first question will be discussed using the externality model, where sea lice will be discussed as biological pollution. Secondary data will be used to summarise the estimations made in different studies evaluating the damage from sea lice

that is borne by society. Current estimates of the abatement cost (before green licences) will also be analysed from the secondary research data. The efficient level of pollution (social optimum) will be reviewed theoretically, together with the target level of pollution used in regulations, including “green” licences. In other words, the study will look at how the sea lice problem fits into the externality theory and its core concepts.

The second research question will be also interpreted in connection to the theory. Different ways of achieving target level of pollution will be discussed in relation to sea lice. These will include command-and-control, and market-based instruments. The data here will mainly consist of the legal documents (regulations) and published releases from the industry discussing different policies and rules. Possible measures that have not been realized in the sector, such as tax on pollution, will be reviewed from a theoretical perspective. Recent proposals by the Ministry of Trade, Industry and Fisheries will be analysed via the framework of the social optimum concept.

The third question is more empirical. The main source of data will be the allocation results showing the technology choices of the aquaculture firms. It will be demonstrated how different abatement technologies influence the abatement costs of individual firms from which the aggregated cost curve can be derived for management purposes. Data on the properties of technologies and abatement effects will be gathered from the research reports. These will be discussed in the context of costs associated with the use of technologies or production methods. The costs include investments, additional operating costs, possible production loss and benefits. Secondary data for the costs analysis will be obtained from the research papers, reports and official industry publications. The model built for the third research question with all of the assumptions will be described in Chapter 3. The results of the analysis will be discussed with the aim of understanding how different technology might affect the form of the aggregated abatement cost curve, and how this information could contribute to the development of pollution control policy in the sector.

## **1.4 Structure of the thesis**

As mentioned above, the study is concerned with the economic information that the “green” licences regulations provide. The regulations will not be discussed in terms of social impact. Ecological effects will only be examined in monetary terms. It is important to be aware that economic considerations are not the only ones to be taken into account when designing environmental instruments.

Another important limitation of the thesis is that only the sea lice problem is studied. Other externalities mentioned earlier are also important, especially the escape problem, but due to the time limit it was only possible to focus on one issue. As was said earlier, the principle of applying externality theory can be used with necessary adjustments to this problem also in further studies.

The paper is organised in the following way. The next chapter provides an overview of the development of Norwegian salmon aquaculture and the problem of externalities. The allocation of “green” aquaculture licences introduced by the government in 2013 will be reviewed. Emphasis will be placed on the role of these regulations as an experiment.

Chapter 3 describes the methods, models and data used for answering research questions. Assumptions and limitations will be described there in more detail.

The research questions are discussed in Chapters 4 and 5. The analysis of the sea lice problem as an externality will be performed. The damage and abatement costs of sea lice pollution and possible point of social optimum will be studied. Chapter 4 will also look at different options for pollution control in relation to types of instruments. Empirical assessment of the farm-level abatement costs in relation to different technologies is performed in Chapter 5.

In Chapter 6 the findings are summarised and analysed in connection with current and possible future regulations.

# Chapter 2: Environmental challenges in Norwegian aquaculture

## 2.1 Aquaculture development: growth versus environment

This section briefly describes the development of the salmon farming industry in the country, in order to provide a background for understanding the origin of the environmental challenges and the factors that currently influence decision-making in this sector.

### Production process

The Norwegian aquaculture sector today is mainly represented by Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) production. Other species (cod, halibut, lumpfish, shellfish, Arctic char) are also cultured in Norway, but they will not be considered in this study since their share of the whole production value is just about 1% (Hovland, 2014). Salmon is an anadromous species, which means that its lifecycle begins in freshwater, but it spends most of its life at sea.

The salmon farming process generally comprises four parts (Krogstad & Bugge, 2013): production of genetic material, production of smolt in fresh water, grow-out stage in sea water and fish processing. The whole process from egg to market-size salmon takes 2-3 years. The production of juveniles, which includes hatching and growing till smoltification, is organised in land-based hatcheries. Eggs hatch in approximately 60 days. After that juveniles develop in fresh water for 10-16 months. Smoltification is the process of the synchronised fulfillment of morphological, physiological and behavioural changes enabling the young salmon to survive, grow and thrive in seawater (Strand, 2014). When all the juveniles are smoltified they are transferred to open sea cages. Using light manipulation and other techniques, producers can influence the time of smoltification. A so-called 0-year smolt is only 10 months old and is usually delivered to sea cages in autumn. One-year smolt is transferred to sea six months later (Krogstad & Bugge, 2013).

In sea cages the salmon are fed with formulated feed. Feeding is one of the main daily operations at production sites. Other important processes are health management, environmental control and technical operations, which ensure the stable functioning of all systems at the farm. The fish grow to the market size in 12-18 months (Cermaq, 2014).

## **Development since the 1970s**

The Norwegian salmon farming industry has experienced rapid growth since the 1970s. The success of the industry has been a result of several factors, usually noted as: favorable natural conditions, effective technology, competence and infrastructure development together with global demand for salmon.

According to (Asche & Bjørndal, 2011) natural conditions and good infrastructure were the main factors in the success of the industry. Farms were spread along the coast in fjords, sheltered from the open sea. Relatively stable water temperatures ranging from 4 to 15°C provided optimal conditions for salmonids. However, the ideal nature conditions were not enough to creating a profitable industry until technological innovations were in place. The central factor in creating the Norwegian salmon production model was introduction of the open sea cage technology in the early 1970s, which opened huge potential for production growth (Hovland, 2014). Before that, rainbow trout was produced at small scale using pond technology or stationary constructions in sea water. The floating cage was first introduced for aquaculture purposes by brothers Grøntvedt at Havlaks AS on Hitra (Møller & Haaland, 2014). The new farming method had a number of advantages. It was easy to build and had a relatively small weight. At the same time the cage was robust enough and of bigger volume than constructions used before. The floating cage allowed the maximum exchange of water and its round shape was better adapted to the swimming behaviour of the fish. The cage was also a relatively low-cost solution. These advantages determined the breakthrough in the industry and its transition from land-based to marine fish farming (Møller & Haaland, 2014).

At the same time there was a shift from rainbow trout to salmon production, driven by profitability reasons. This is largely due to better growth performance, and also because it is easier to have Atlantic salmon available for the market at all times of the year (Asche & Bjørndal, 2011). Salmon was also better accepted on the market and from the 1970s Norwegian marine farming developed as a monoculture oriented to the global consumer.

Science and technology was also oriented to effective salmon production. Sea cage technology was improved, and the entire production process, from smolt to market size salmon, was steadily modernised. Major developments occurred in the production of fish feed and feeding techniques and in the controlled smoltification process. As described by Hovland (2014), the 1980s were the first big expansion period in Norwegian aquaculture, as a result of an increased number of licences and their volume as well as easier access to smolt. By the end of the decade, however, the crisis symptoms were obvious, caused not only by the market situation but huge losses due to fish



diseases. Introduction of vaccines against salmon diseases was a major step in overcoming the crisis and increasing productivity. The role of vaccines in production growth in the 1990s is demonstrated by Figure 1: the significant decrease in the usage of antimicrobial agents in Norwegian aquaculture in the period 1987 to 1996 is mainly attributed to the introduction of effective vaccines against bacterial diseases in Atlantic salmon and rainbow trout, and to improved health management (NORM/NORM-VET, 2011).

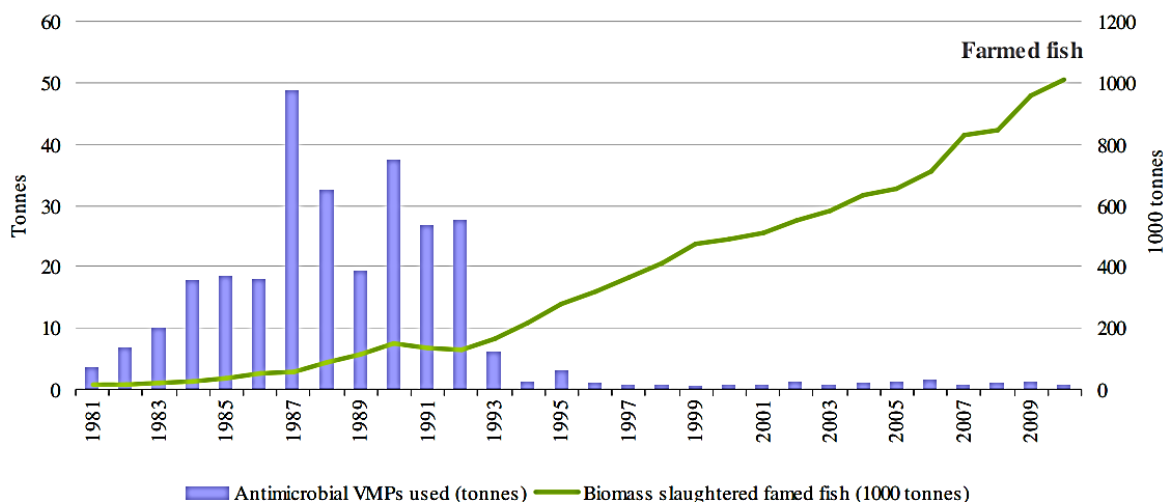


Figure 1. Total sales of antimicrobial veterinary medicinal products (VMPs) for therapeutic use in farmed fish in Norway in the period 1981-2010 versus produced biomass farmed fish. Source: NORM/NORM-VET (2011).

Apart from disease control, the national breeding programme for salmon played an important role. Farmed salmon is a specific species, formed by years of breeding populations that originated from 41 Norwegian rivers (AquaGen, n.d.). Selection was made for over 20 different characters, including growth rate, resistance to diseases and stress, feed conversion ratio, age at maturation, and adaptation to fresh and seawater. It is important to stress the importance of science and technology in dealing with biological challenges at the beginning of aquaculture development (introduction of the open sea cage) as well as in the transition period. The economic challenges that restricted growth in the industry, on the other hand, required market-based solutions.

Further development depended on access to capital that small-scale producers did not have (Hovland, 2014). Structural transition leading to more effective large-scale production took place in the early 1990s. (Asche, Roll, Sandvold, Sørvig, & Zhang, 2013) analysed the concentration and increasing size of companies in this period. The ownership constraint in Norway was removed in 1992, and a process of mergers and acquisitions commenced. Economies of scale had been exploited

and the industry in the early 1990s could be characterised by constant returns to scale. The removal of the ownership restrictions enabled firms to start operating more than one licence at one location. Companies started to operate several licences on a single farm when there was sufficient environmental carrying capacity. This also led to a significant increase in the size of cages (Asche, Roll, et al., 2013).

The combination of factors and processes named above made Norway the largest producer of salmon globally. The production of cultured salmon reached 1.17 million tonnes in 2013, and rainbow trout 71.6 thousand tonnes (SSB, 2014). The total number of aquaculture licences for salmon and trout (grow-out stage) was 959 by 2014. These licences are owned by 159 registered companies (Directorate of Fisheries, n.d.). According to the Directorate’s statistics, there were 575 farms (locations) in Norway by the end of 2014, which corresponds to a total of 3688 cages with salmon and trout.

Nearly all the salmon produced is exported. In 2014 Norway exported 999 000 tonnes of cultured salmon and 50 700 tonnes of rainbow trout. Due to high prices the value of exported salmon reached record 43.9 billion NOK (Norwegian Seafood Council, 2014). Norway exports farmed salmon to more than 100 countries. An import ban on European seafood products in Russia, which used to be a major market for Norwegian seafood, did not affect export too much as it was compensated by increased demand from other countries. Today, Poland is the largest export market for Norwegian salmon. Generally, the EU represents 74% of the export value for Norwegian salmon. The USA and Asian countries, especially China and Japan, are also important markets.

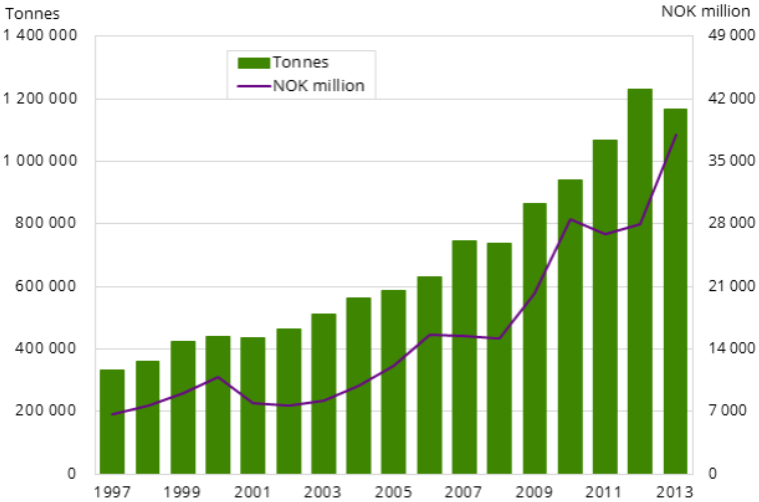


Figure 2. Sales of salmon. Quantity and first-hand value. 1997-2013. Source: SSB (2014).

Figure 2 shows the development of sales in terms of volume and value from 1997 to 2013 (including the domestic market). As seen from the graph, sales increased steadily.

Sales follow demand on the global market, which is rising 13% every year on average (Aandhal, 2014). Production growth is needed to satisfy this demand and therefore maintain the market share. Norway's main competitor on the salmon market is Chile, where the harvest of farmed salmonids (mainly Atlantic salmon, rainbow trout and Coho) reached 876 thousand tonnes in 2014 (Clement, 2014). Other major salmon producing countries are the United Kingdom (5% of global supply in 2013), Canada (5%) and the Faroe Islands (2%).

Maintaining the market share is important for the Norwegian economy. According to SSB (2015), seafood export accounts for only 7% value of all exports (and aquaculture products prevail over exports from capture fishery). Nevertheless, the socio-economic role of the industry is significant. The aquaculture sector contributed to 8.41 billion NOK of the Norwegian GDP in 2012 (Ministry of Trade, Industry and Fisheries, 2015) . Around 5500 people are directly employed in aquaculture production, about 3000 work in the sale and distribution of farmed fish, and other industries connected to the sector employed around 21,000 in 2012 (Ministry of Trade, Industry and Fisheries, 2013). Production sites are located all along the coast providing employment opportunities in municipalities. Growth in the aquaculture sector is therefore important for the country's competitiveness and creating new working places.

The key problem of the industry growth today is that the potential for intensive growth has been exhausted, and extensive growth is limited due to environmental challenges and coastal space conflicts. Until now salmon production has been increasing both extensively (by increased number of production facilities) and intensively (due to productivity growth). As mentioned earlier, the development of technology and production methods has driven much of the growth. According to Asche and Bjørndal (2011), the significant increase in output, especially during the 1990s, was not matched by a corresponding increase in the number of production sites (between 1985 and 2002 no new licences were issued). More effective production in terms of feeding routines and disease prevention, has improved feed conversion ratios, shortened the on-growing period and lowered mortality rates. There has also been a movement of production from sheltered locations, where pollution is a problem, to more exposed locations. As a result, the output per licence increased and production costs fell. From 1990 to 2008 the industry nearly quadrupled its production. Production

has expanded fairly steadily, with brief pauses in 1986–1987 due to severe disease problems, and in 1990–1992 and 2001–2002 due to problems with profitability (Asche & Bjørndal, 2011).

The contribution of technical and technological improvements is no longer the dominant factor, however. As shown by (Asche, Guttormsen, & Nielsen, 2013), the yearly growth in Norwegian salmon production has slowed from 15–20% in 1992–1995 to 1–2% over the period 1996–2008. Total factor productivity change was estimated at 1–2% a year, where the contribution from technical efficiency change is between 0.2 and 1.2% and technological change is between 0.6 and 0.8%.<sup>2</sup> Most of the production growth from the late 1990s has mainly been due to higher input, which means more licences and larger plants at each location. It is noted that further expansion of the industry is problematic due to the scarcity of suitable production sites, and environmental concerns that are increasingly leading to the regulation of farm size.

Although coastal space is an important limiting factor for the aquaculture sector, this work is concerned entirely with the environmental factor. The key environmental challenges in salmon aquaculture industry are described below.

## **2.2 Environmental externalities as a growth limiting factor**

Asche and Bjørndal (2011) described two main categories of environmental issues occurring as a result of aquaculture production growth. Global challenges are mainly associated with the “fish meal trap”: increased demand for feed from a growing aquaculture production is believed to increase fishing pressure on wild stocks and consequently threaten the sustainability of the associated capture fisheries, since marine protein and oils are important ingredients of the diet for cultured seafood.

A second group of issues – local ones – include organic pollution from farming sites, chemical pollution from feed waste, antibiotics and other treatment stuffs, destruction of local habitat, the spread of pathogens and interaction of farmed fish with local stocks. Both global and local impacts are present in Norwegian salmon farming and are limiting factors for production growth.

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<sup>2</sup> Technical efficiency change means increased production output with the same quality of inputs, while technological change is defined as improvement in quality of input factors (Asche & Bjørndal, 2011).

## **Global issues – “fish meal trap”**

The issue of the unsustainable fishing of wild pelagic stocks in connection with increasing demand for aquafeed is widely discussed and quite controversial. The salmon farming industry has been criticized for being a net consumer of marine resources, in the form of fishmeal and fish oils used in feed, and their dependence on wild stocks has been highlighted. As noted by Asche and Bjørndal (2011), the extent to which the fish meal trap represents an environmental problem depends on whether increased aquaculture production actually increases the fishing effort on species that are used for fishmeal and fish oil production. This, in turn, depends on fisheries management, market conditions and the development of substitutes for fish protein and oil.

The majority of the world stocks of pelagic marine fish is considered to be either fully or over-exploited (FAO, 2012). Among others, Deutsch et al. (2007) concluded that there was an increasing dependence of Norwegian aquaculture on one marine ecosystem, the southeastern part of the Pacific Ocean, in the period 1980-2000, which indicates the increasing exploitation of pelagic stocks in this region. As the major stocks are exploited, further growth in aquaculture production requires a reduction in reliance upon fish meals and oils rendered directly from these sources, and the increasing use of alternative feed ingredients. Possible alternatives are vegetable proteins and oils, by-products from fish and terrestrial animal processing industries, organisms from lower trophic levels and bacterial and algal proteins and oils produced by industrial fermentation technologies (Bendiksen, Johnsen, Olsen, & Jobling, 2011). Shepherd and Bachis (2014) compared estimated 2000 and 2012 fish oil inclusion rates in Norwegian farmed salmon and showed that over this period fish oil inclusion has fallen to approximately one third of what it was twelve years previously (before the substitution with rapeseed oil began).

Despite the efforts made to replace marine fish ingredients with alternatives such as vegetable proteins and oils, the balance between the use of wild fish and salmon production is still generally negative, with calculated fish in–fish out values often being over 4 (Bendiksen et al., 2011). Although there is a potential for salmon farming to move from a position as net consumer towards that of net producer of fish protein, it has not yet been achieved. A number of studies have been carried out to examine the effect of replacing fish meals and fish oils with alternative ingredients in fish feeds. According to Bendiksen et al. (2011), the most frequent finding is that partial replacement is possible without compromising growth, but complete replacement is usually not successful. This means that so far the “fish meal trap” represents an environmental concern and a potential constraint on salmon production growth.

## **Local issues – organic waste**

Organic waste from salmon farms consists of particles and soluble ionic compounds. Fish feed waste and faeces are released into the environment in form of particles. Ionic compounds are the products of the fish metabolism, mainly phosphor (phosphate) and nitrogen (nitrate, nitrite, ammonia) dissolved in the water (IMR, 2014).

The spread of organic particles depends on the currents activity and depth at the production site. In fjords the deep water exchange might be low, so that the particles accumulate on the sea bed as sediments and increase organic load. Decomposition of organic sediments causes gas production that is poisonous for local fauna including fish in the cages. There is particular concern regarding the influence of organic sediments on vulnerable benthic organisms. Another effect of accumulated organic particles is that in open systems other marine animals are attracted to fish farms for feeding on waste. It is not yet known how this affects ecosystems (IMR, 2014).

Metabolic waste, excreted by fish via gills and kidneys, is released directly to the environment, resulting in a high ammonia concentration in close proximity to the cages. With low water exchange this might result in the increasing growth of unwanted microalgae and lead to eutrophication.

The estimated emission from salmon farms in Norway is 14,000 tonnes nitrogen and 22,000 tonnes phosphor annually according to the report. Pollution has the strongest effect just under or close to the production site if the water exchange is insufficient. In areas with stronger currents organic waste does not have a significant impact.

Asche and Bjørndal (2011) underline the role of improvements in fish feed production and feeding techniques in addressing the organic waste problem. The increased inclusion of lipids in feeds and a more effective use of pellets has reduced organic waste over the last two decades, however, according to IMR (2014) further reduction of waste per unit production is unlikely. Another major factor in preventing waste accumulation is moving production sites to more exposed areas. Most salmon farms are now located in areas with relatively strong currents, deep water and suitable seabed topography.

From 2005 all fish farms in Norway were obliged to monitor the conditions of the seabed under cages in order to prevent environmental damage from organic waste (Norwegian Environmental Agency, 2014c). Despite all the concerns, organic waste does not seem to represent a major limitation to the growth of salmon production at the moment.



## **Emission of chemicals**

Sources of chemical emissions from salmon farms are stuffs used for fish treatment, technical operations and the polluting components of fish feed. Some of these chemicals accumulate in marine organisms and are poisonous (IMR, 2014). Cadmium released from waste food pellets is on the priority list of the environment authorities. The use of cobber for cleaning nets is another major concern. According to the Norwegian Environmental Agency (2014a), 1061 tons of cobber was used for this purpose in 2013.

Antibiotics used in fish disease treatment is also a source of environmental pollution. These chemicals usually affect the area close to farms. Although harmless to marine organisms in themselves, antibiotics might cause the development of resistant bacteria (IMR, 2014). As shown previously in Figure 1, the use of antibiotics was particularly high in the 1980s, before the vaccines against cold water vibriosis and furunculosis were introduced. Since the late 1990s the use of antimicrobial agents has been stable and low. In 2011 only 500 kg of active substance were used in Norwegian aquaculture. In 2012, however, the use of antibiotics increased three times, responding to a bacterial disease outbreak. In spite of variations, the use of antibiotics in fish farming in Norway remains relatively low. As concluded in a report by the Norwegian Veterinary Institute (Johansen, 2013), samples from aquaculture sites in Norway showed no increase in bacterial resistance in 2012.

The use of chemicals for sea lice treatment has been in contrast a great concern in recent years. The total use of treatment stuffs has increased significantly from 2009 (Norwegian Institute of Public Health, 2013). Among these chemicals flubenzuron emissions are the most dangerous to the environment. Their effect on sea lice is based on the ability of flubenzuron to hinder chitin shell growth in crustaceans. The chemical was reported to cause mortality in other crustaceans (crabs, prawns) around salmon farms (Norwegian Environmental Agency, 2014b).

The tripling of hydrogenperoxide use in 2013 is explained first of all by the development of resistance in sea lice to other chemicals (NFSA, 2014a). Resistance is another dangerous effect which makes the problem of chemical emission particularly serious. In order to eliminate the damage from chemicals, the initial problem - sea lice spread - should be addressed.

## Salmon lice

Sea lice (Copepoda, Caligidae) have been the most widespread pathogenic marine parasite in the Atlantic salmon farming industry worldwide, and in the past two decades pathogenic infestations of wild salmonids have escalated. Wild Atlantic salmon are parasitized by two species of sea lice: *Lepeophtheirus salmonis* and *Caligus elongatus*. The first has the greatest impact on Norwegian salmon farms, while *Caligus* occurs on farms in British Columbia, Chile, Europe and Japan (Costello, 2006). Although challenges can also arise from the species *Caligus elongatus*, such infections are less common and more predictable. Consequently, most control programs for sea lice focus on *L. salmonis* populations.

The lifecycle of this parasite includes infectious and immobile stages (Figure 3). Being an ectoparasite, it easily infects new hosts in the water. Salmon lice hatch from the eggstrings carried by the adult female as planktonic nauplius larvae. There are two planktonic and free-swimming nauplius stages and third moult is to the copepodid, which is the infective stage when the parasite must find a host fish. Once attached to a host, the copepodid moults into the first of two attached chalimus stages, followed by further moults to the preadult stages and the definitive adult phase (Thorstad et al., 2014).

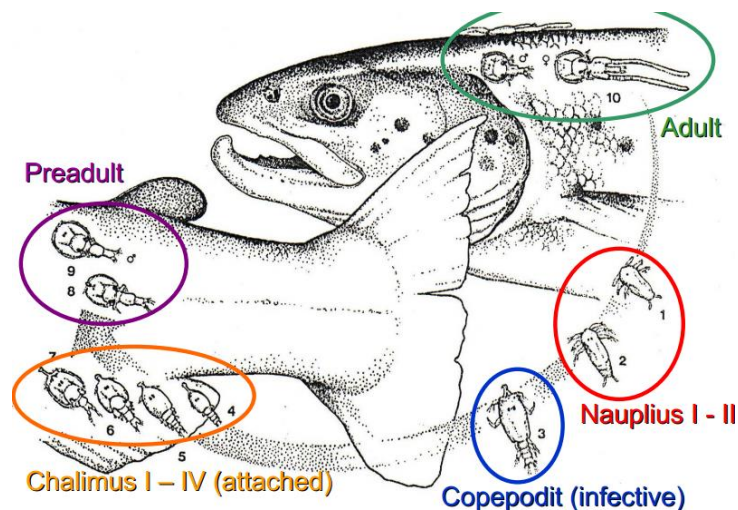


Figure 3. Lifecycle of salmon lice. Source: Kristoffersen (2014).

Salmon lice feed on the skin, blood and mucus of salmon. Apart from mechanical damage the infection affects the osmoregulation balance of the fish. The parasite affects the growth, swimming and reproduction and immunity of salmon. Osmotic stress can result in mortality if a fish is heavily

infected with lice. Physiological effects are documented for Atlantic salmon, sea trout (*Salmo trutta*) and Arctic char (*Salvelinus alpinus*). Salmonid individuals seem to have different genetic resistance to sea lice infection (Anon., 2012).

The year-round high density of hosts provides the ideal conditions for salmon lice. The parasite produces large amounts of planktonic larvae that are spread via water currents and can infect migrating wild Atlantic salmon smolts, as well as sea trout and Arctic char that stay in coastal waters (Taranger et al., 2014).

Sea lice are present naturally in the marine environment, and historically the parasite has been observed in rather low numbers on wild salmonids. Since the late 1980s, however, there have been several reports of increased sea lice infections of salmonids in Norway, Scotland, Ireland, and Canada. In the 1990s, sea trout in salmon farming areas along the coast of Norway were observed returning to rivers shortly after they had migrated to sea (Finstad et al., 2010). These prematurely returning sea trout were heavily infested with salmon lice and had to return to a fresh water environment where sea lice do not survive. The opportunity for feeding and growth in marine water, however, was lost (Bjørn, Finstad, & Kristoffersen, 2001).

Norwegian investigations in the early 1990s indicated that the infestation of sea lice larvae also occurred on migrating Atlantic salmon smolts swimming through the long and intensively farmed fjords of western and central Norway. Arctic char in northern Norway were probably also subject to heavy infestations in areas with salmon farms (Finstad et al., 2010).

To what extent salmon farming has contributed to the stock decline of wild salmonids is a subject of debate. According to Finstad et al. (2010) it seems likely that salmon lice epidemics may be partly responsible for the decline of certain populations of wild anadromous salmonids along the Norwegian coast. The same conclusion is found in the NINA report (Thorstad et al., 2014). The overall result of the studies included in the report suggests that salmon lice have a potentially significant effect on the marine survival of Atlantic salmon. It has also been concluded that salmon farming increases the abundance of lice in marine habitats and that the parasite in intensively farmed areas has negatively affected wild sea trout populations. According to the report, premature migratory return, increased marine mortality and reduced growth of survivors implies a reduction in the numbers and body size of sea trout returning to freshwater for spawning, which in extreme cases could result in the local loss of anadromous sea trout populations.

Torrissen et al. (2013), however, note that correlation between declining salmon stocks and growth of aquaculture does not necessary mean causation. They suggest that the disagreement about

the scale of the impact of salmon lice on the decline of wild salmon populations arises partly from a lack of good data.

Although the relationship between wild stock abundance and sea lice is not known exactly, the farm density factor is not disputed. Costello (2006) reported host abundance and distribution as one of the key factors affecting the spread of sea lice along with sea water temperature. A concentration of hosts on salmon farms has increased lice abundance locally, which led to lice infestations on farmed and wild hosts.

The role of salmon farms in “production” of sea lice is noted in a number of recent reports and studies (e.g. Anon., 2012; Jansen et al., 2012; Taranger et al., 2014). Jansen et al. (2012) draw attention to the positive association of local biomass density with both sea lice abundance and control efforts, and concludes that sea lice represent a density-dependent negative feedback mechanism that may limit growth in salmonid farming in Norway. The “emission” of salmon lice by farms and the potential production output limits as a consequence, suggest that the parasite can be seen as an externality, or pollution, produced by salmon aquaculture industry, and partly internalized. This concept will be discussed in Chapter 4.

The limitation of salmon production as a consequence of sea lice abundance has already been imposed in form of environmental controls in Norway. One of these measures was the establishment of the Norwegian National Salmon Fjords (NNSF), which are protected fjord areas in which salmon farming is prohibited (Finstad et al., 2010).

The routine monitoring of sea lice on Norwegian fish farms is imposed by regulations. From 2009 the regulations require that the average number of lice on each salmon in a net pen shall not exceed 0.5 adult female lice per fish. Sea lice numbers are reported to the Norwegian Food Safety Authority (NFSA). In addition, mandatory and synchronised delousing is planned along most of the Norwegian coastline to reduce infestation pressure during the spring run of wild salmonids. Several chemicals are licenced and routinely used for lice treatment in farms, however, as mentioned earlier, increasing observation of the treatment failure of the most used medicines in Norway is of considerable concern. The need for new methods is increasing due to developing resistance in lice.

According to the report by NFSA (2014b), salmon lice abundance remained high at farms in the recent three years, as demonstrated by Figure 4.

Figur 1: Gjennomsnitt av voksne hunnlus pr fisk på landsbasis

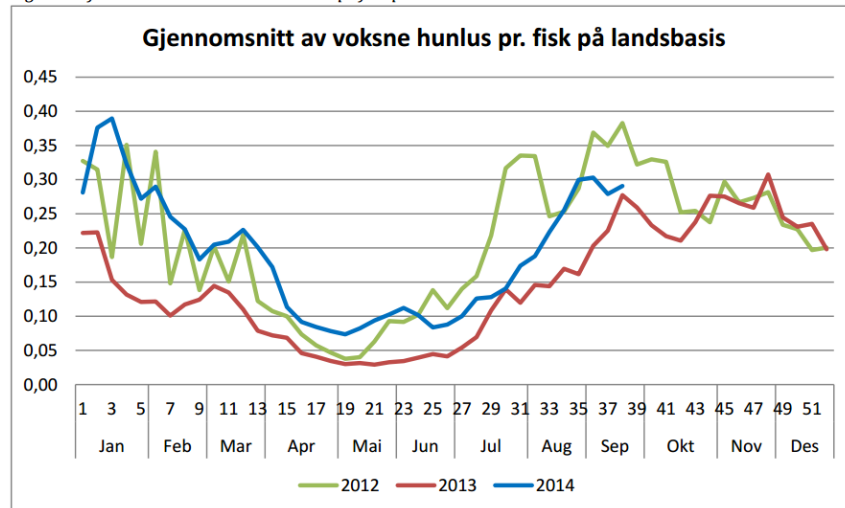


Figure 4. Average salmon lice level at Norwegian salmon farms, adult female lice per fish. Source: NFSA (2014).

As shown in the figure, salmon lice levels in 2014 remained under the maximum. The authority reports that to keep the lice spread under control in high temperature conditions more treatments were made, which resulted in the extensive use of chemicals and reduced fish welfare. Despite the delousing, infestation of the wild trout was high.

### Other fish diseases

According to (IMR, 2014) diseases in farmed fish (viral, bacterial and parasitic) are a risk for wild populations as they are spread via water, contact with escaped fish or with pathogen-carrying parasites. There is additional risk for environment when exotic pathogens are transported with smolt or eggs for aquaculture purposes. An example of this type of transmission is the introduction of *Gyrodactylus salaris* into Norwegian rivers, which causes mortality in wild salmon juveniles. As for viral and bacterial diseases, it is not known to what extent fish diseases from salmon farms affect wild fish and therefore, there is much uncertainty in assessing risk to the environment. Overall risk is considered to be low in the IMR report with the exception of the sea louse parasite.

Sea lice and other pathogens can be carried by escapees, however, escaped fish are not only dangerous as disease carriers. The escape of farmed fish is another major factor limiting growth in the aquaculture sector.

## **Farmed fish escape**

Fish escapes from open sea cages are the result of a variety of incidents related to farming equipment and its operation. According to Ø. Jensen, Dempster, Thorstad, Uglem, and Fredheim (2010) escapes of Atlantic salmon reported to the Directorate of Fisheries in the period 2006-2009 were predominantly caused by structural failures of equipment (68%). Other common reasons were operational related failures (8%) and external factors (8%). Structural failures may be caused by icing, strong winds, waves and currents. Most large-scale escape events (>10 000 individuals) occur in the autumn months when coastal storms are most frequent and intense.

Naylor et al. (2005) summarised the environmental risks associated with escapes of farmed Atlantic salmon. First of all, there is a risk of competition with wild fish for mates, space, and prey. Escaped salmon can spawn successfully in rivers. As a consequence escaped individuals may directly disrupt the spawning of wild salmon. Farmed fish might destroy the spawning grounds of wild fish, for example, and the spawning of wild females with farmed males may also result in poor fertilization of eggs. The successful reproduction of farmed salmon in the wild, or the escape of juveniles from freshwater facilities can lead to further interaction between wild, farmed, and hybrid fish in fresh water. The potential for competition is significant because the diet and habitat choice of farmed and hybrid juveniles overlap with those of their wild conspecifics. Naylor et al. (2005) notice that farmed offspring have a size advantage and, potentially, a competitive edge over wild juveniles. Territorial and social dominance behaviour in salmonids means the addition of cultured fish to wild populations can lead to space competition in fresh water and affect both mortality and growth of the wild fish. In the marine environment the presence of large numbers of escaped farm salmon in coastal ecosystems is likely to increase competition for available resources as introduced fish consume wild food items and occupy space.

Earlier studies of the genetic effects following releases of nonnative salmonids showed that the genetic effects on natural populations are often unpredictable and may vary from no effect to complete displacement. It has also been concluded that genetic effects on performance traits always appear to be negative in comparison with the traits of native populations. Interbreeding between wild and farmed fish can result in a mixing of gene pools if the hybrids can reproduce, and eventually can lead to a wild population composed entirely of individuals descended from farm escapes. The result, as concluded by Naylor et al. (2005), would be an irreversible loss of the unique genetic diversity of wild salmon and hence of their capacity to adapt to environmental change.



As noted earlier, escaped salmon might represent possible disease transmission routes in the environment. Salmon lice transmission is one of the main concerns (Bjørn et al., 2001). Naylor et al. (2005) also note the possible transmission of the furunculosis disease and ISA to wild stocks.

Taking all the environmental risks into account, the fish escape problem is highly prioritized in aquaculture management. According to the regulations (Akvakulturdrifts forskriften, 2008) escape episodes should be reported to the Directorate of Fisheries. Figure 5 shows the reported numbers of escapees in the period 2001-2014.

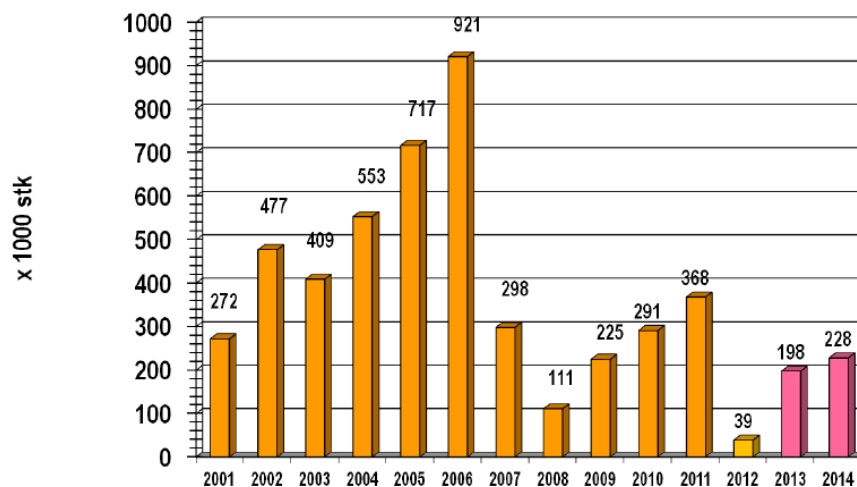


Figure 5. Escaped farmed salmon, registered in 2001-2014. Source: Directorate of Fisheries (2014b)

As seen from the figure, the number of reported escapees dropped significantly in 2007, which was possibly a result of an action plan implementation (Directorate of Fisheries, 2007), however, according to (IMR, 2014) official figures do not cover all the episodes. Not all the escape incidents are reported. It is also difficult to estimate the number of escapees in each case.

### 2.3 Looking for solutions – the “green” licences experiment

Aquaculture in Norway is regulated by the Ministry of Trade, Industry and Fisheries through the Directorate of Fisheries. The main regulative document for the sector is the Aquaculture Act (2005), which refers to other laws and regulations issued by ministries. Along with the Directorate, the industry is controlled by NFSA, the Norwegian Environment Agency, Norwegian Coastal Administration and Norwegian Water Resources and Energy Directorate. All these authorities regulate environmental issues including the situation with salmon lice and the escape problem. As

noted earlier, salmon lice levels are reported to the NFSA, and the escape episodes are reported to the Directorate of Fisheries. In both cases a salmon production company meets certain responsibility even withdrawal of approved location in the most serious cases (Ministry of Trade, Industry and Fisheries, 2014). Nevertheless, it has not yet been possible to control these challenges under existing technologies and production methods. At the same time, the salmon farming industry requires the potential to expand production for the reasons explained in the beginning of this chapter.

According to the Aquaculture Act a licence is required for establishing and operating a salmon farm. The allocation of new licences is made in separate rounds, with special regulations issued each time. As concluded above, the potential for productivity growth has been almost fully exploited at the moment. An increase in production output is thus only possible by issuing new licences or increasing the maximum biomass (MTB) for each licence.

In 2013 a new allocation process began, when 45 aquaculture licences were issued (Forskrift om løyve til havbruk med matfisk, 2013). The idea of the regulations was to meet both environmental and economic objections, which is formulated in the document as follows:

“The regulations shall contribute to facilitation of sustainable and competitive aquaculture that will add to the activity and value creation along the coast, and to stimulating of realization of new technological solutions or production methods that lead to reduction of environmental challenges such as fish escapes from the farms and spread of salmon lice”.

“Green” licences were distributed in three groups (Table 1). The general requirement for all applicants was an obligation to apply a new technological solution or production method that reduces the environmental risk of sea lice spread or fish escape. The technology or method should be new, which means that it has not been in commercial use previously. The effect of these methods on the reduction of salmon lice infestation to a certain level (0.25 or 0.1 adult female lice per fish) should be documented. No indicators were provided for escape prevention.

As shown in the table, 20 licences were issued only for Finnmark and Troms in group A, unlike the other two groups where licences were distributed regardless of location. The requirement regarding salmon lice was that proposed technology provides an infestation level under 0.25 lice per fish at all times. For both Groups A and B the owner of a new licence had to use the same “green” technology for one of their previous licences. In Group C this requirement was not introduced, however, stricter criteria were given for sea lice levels (0.1 lice per fish) and escape risk reduction (the risk should have been reduced “significantly”). Applicants for licences in Groups A and C paid a fixed price of 10 million NOK per licence when approved.

Table 1. Green licences allocation groups

|  | <b>Group A</b>          | <b>Group B</b>  | <b>Group C</b>                                      |
|--|-------------------------|---|---|
| <b>Region</b>  | Finnmark and Troms      | All regions   | All regions   |
| <b>Number of licences</b>                                | 10 Finnmark<br>10 Troms | 15  | 10  |
| <b>MTB (max biomass, tonnes per licence)</b>             | 945                     | 945 t for Finnmark and Troms<br>780 for other regions     | 945 for Finnmark and Troms<br>780 for other regions |
| <b>Sea lice restrictions, adult female lice per fish</b> | 0.25                    | 0.25  | 0.1   |
| <b>Reservation of one existing concession</b>            | Required                | Required  | Not required  |
| <b>Price, NOK per licence</b>                            | 10 million              | Open auction with pre-qualifying process<br>55-66 million | 10 million  |

For applicants in Group B, no fixed price was given. Instead, 15 licences were auctioned among pre-qualified participants. Requirements for pre-qualification were the same as in Group A, but the winners in this case were not those with the best technology, but those with the highest bid.

The number of applications (255 in total) by far exceeded the number of licences issued; the allocation was then based on the decision of an expert group who had to choose the best applications in Groups A and C and organise the closed auction for Group B. The decisions of the working group were disputed by the public as was the regulation design and organisation as such, however, socio-political issues are beyond the scope of this thesis. In the framework of this study it is important to explain why the allocation of “green” licences was not a solution to the “growth vs. environment” problem.

First of all, the regulations do not cover the entire industry. For production sites allocated before 2013 there were no requirements to change technologies to “greener” ones. Secondly, it was not a long term solution. In addition, the effects of technologies and the methods proposed by the applicants are yet to be seen. Finally, the principle of a criteria-based allocation of licences does not

provide predictable growth, which makes it difficult for businesses to plan investments and development. The need for a long-term policy that will provide sustainable growth is recognised by the Ministry of Trade, Industry and Fisheries, and new concepts are to be determined in 2015 (Furuset, 2014a).

In this respect, the role of “green” concessions as an experiment is important. Although not a solution in itself, the allocation results give valuable information for future development of environmental regulations in the aquaculture sector. In this thesis the results of the allocation will be analysed from the environmental economics perspective. The main argument here is that after the regulations were implemented, the costs of sustainable production became available, since the technology choice and associated costs are to be known for all 45 new licences. In the terms of the externalities theory, there is now more data accessible for deriving abatement cost function for salmon lice and for the escape problem. Both types of environmental impact can be studied as externality problems, but in this study only the sea lice challenge will be considered. The method is described in the next chapter.

## Chapter 3: Data and methods

### 3.1 The theory of externalities

The problem of salmon lice will be examined from the perspective of externalities theory. In this context, salmon lice production by aquaculture industry is considered as pollution, and therefore the instruments of pollution control that can be applied to reduce salmon spread in the environment will be discussed in terms of achieving social optimum in a purely economic sense. This means that the political and technical constraints of enforcing such instruments are not considered at this stage. In this chapter the theoretical background is given with an emphasis on those elements of pollution control theory that are relevant for the studied problem, while in following chapters the salmon lice challenge will be analysed in the framework of this theory.

First of all, it is necessary to give definitions of externality and pollution. As defined by Perman et al. (2011, p.121), “an external effect, or an externality, occurs when the production or consumption decisions of one agent have an impact on the utility or profit of another agent in an unintended way, and when no compensation (payment) is made by the generator of the impact”. A harmful externality is usually referred to as ‘pollution’.

Helfand, Berck, and Maull (2003) define pollution from both a physical and economic perspective. The unavoidable character of effluent generated due to the physical nature of the production process is underlined. Pollution can be said to arise from the laws of nature. Byproducts, either materials or wasted energy, are a joint part of a production process due to the conservation of mass and energy and the increasing entropy of systems.

A physical production process can also be described in terms of price and cost information. It is possible for a producer to reduce emissions, and, therefore, harmful effects, however, when abatement levels get very high, abatement costs increase. From an economic perspective, there is pollution because it is costly not to pollute.

Another important element is the classification of pollution nature. Perman et al. (2011) define flow-damage and stock-damage pollution. In pure cases of flow-damage pollution the damage will immediately drop to zero if the emissions flow (the rate of discharge) becomes zero. Stock-damage pollution describes the case in which damages depend only on the stock of the pollutant in the environmental system at a given time point. For a stock of the pollutant to

accumulate, it is necessary that the residuals have a positive lifespan and that the emissions are being produced at a rate which exceeds the assimilative capacity of the environment.

The relationship between the accumulation of pollutant, natural assimilative capacity and the rate of emission is demonstrated by Flåten and Skonhoft (2014). As shown in Figure 6, the function of environmental capacity to “clean up” a pollutant,  $F(X)$ , is positive until the accumulated quantity of this pollutant  $X$  is lower than  $X_K$ . If  $u_t = u$  is the constant level of emissions, the model has two equilibriums. At the given level of accumulated residuals  $X_L$  the stable equilibrium is achieved, since the difference between emission rate and assimilation will bring the level of accumulated pollutant to  $X_L$ , if the initial level is either less than  $X_L$  or lies between  $X_L$  and  $X_H$ . At the given initial accumulated pollution  $X_H$  the unstable equilibrium is achieved. This means that at  $X > X_H$  the quantity of accumulated residuals will increase until  $X_K$ , where the environment has no capacity to assimilate the pollutant, and the pollution stock will increase infinitely. Later in this chapter the externality problem will be discussed assuming flow-damage pollutant.

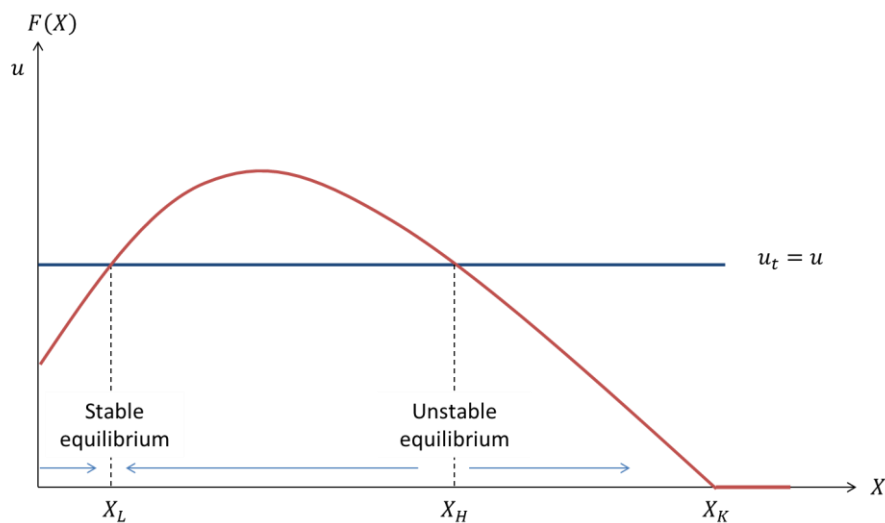


Figure 6. Environmental assimilative capacity as a function of pollution stock. Source: Flåten and Skonhoft (2014).

The basic problem with external effects follows directly from the definition in regard to unintended pollution and lack of compensation/payment. Given the lack of payment, which in a market system will take the form of monetary compensation, an agent will not take any account of the harmful effect concerned. As put by Helfand et al. (2003), the root cause of pollution is the lack of markets in effluent. There are two reasons for this lack of markets. The first is the lack of property rights for a clean environment. The second is the public good nature of effluents. Externalities are then a source of market failure.

Perman et al. (2011) classify externalities as “consumption-consumption”, “production-production” and “production-consumption” types. The first is characterised by externality produced by an individual that affects the utility of another individual, while “production-production” is the case when pollution produced by a firm affects the output of other producers. In both cases an effective solution can be achieved by bargaining according to the Coase theorem. In “production-production” case an alternative way of internalizing the externality would also be to have the firms collude in order to maximise their joint profits. In “production-consumption” case, when multiple individuals are affected by externality produced by industry, intervention by the regulator is needed.

According to Perman et al. (2011), economic behaviour in reality always involves externalities. The market, in the absence of corrective policy, will “over-supply” pollution. The key to dealing with the market failure is to put in place the missing feedback, to create a system which does require the compensation for harmful effects, so that they are no longer unintentional. In order to create such a system, two main questions should be answered:

1. How much pollution should there be? (What is the target level of pollution?)
2. Given that some target level of emissions has been chosen, what is the best method of achieving this level? (What type of pollution control instrument should be chosen?)

### **The concept of pollution target**

Before the concept is described, the modelling framework, including important assumptions should be outlined. The models in this chapter are built for the “production-consumption” externality case, where emissions arising in production adversely affect many individuals in ways that are non-rival and non-excludable.

The models use the flow-damage pollution case, when damage results only from the flow of residuals. The level of pollution is the rate at which it is being discharged into the environmental system. Uniformly mixed emissions are assumed.

Partial equilibrium approach is applied. It is further assumed that conditions for the Coase theorem are not satisfied, which means that the compensation for harmful effects cannot be achieved by direct bargaining, and so the intervention of the regulator is needed to correct for the market failure.

A simple static model – one in which time plays no role – can be used to identify the efficient level of a flow pollutant. In this model emissions have both benefits and costs (damages). Production generates an intended good or service and the associated pollutant emissions. In an

unregulated economic environment, the costs associated with production are paid by the producer, and are thus internalized, but the costs of pollution damage are not met by the firm, and are not taken into account in its decisions, and so are externalities. For simplicity, it is supposed that damage is independent of the time and the source of the emissions, and that emissions have no effect outside the economy being studied.

An efficient level of emissions is one that maximises the net benefits from pollution, where net benefits are defined as pollution benefits minus pollution damage (Perman et al., 2011). The level of emissions at which net benefits are maximised is equivalent to the outcome that would prevail if the pollution externality were fully internalised. In the case of flow pollution, damage ( $D$ ) is dependent only on the magnitude of the emissions flow ( $M$ ), so the damage function can be specified as

$$D = D(M), \text{ measured in NOK.}$$

Since emission reduction requires additional cost, in the form of a reduction of output or an investment in cleaner production methods, there are savings (or benefits) associated with an increase in emissions. These cost savings are regarded as benefits of pollution. This concept of a pollution benefit as the cost of abatement measures avoided by the producer is given in Perman et al. (2011) and will be applied through the thesis. It follows from the concept that the benefit of pollution is equal to the abatement cost. It should be noted that pollution benefits might be also interpreted in terms of associated additional production output (or avoided production cut). In this case the economic trade-off between emissions, material goods and the costs of environmental damage form the cost-benefit model (Flåten & Skonhøft, 2014). The abatement cost is then not necessarily equal to pollution benefit. In this thesis abatement through production cuts is not considered as an option. Thus, the benefit of emissions is seen as avoided abatement cost in form of investment in alternative production methods.

The benefit function is represented symbolically by equation

$$B = B(M), \text{ NOK}$$

where  $B$  denotes benefits from emissions. The social net benefits ( $NB$ ) from a given level of emissions are defined by

$$NB = B(M) - D(M)$$



If  $B'(M)$  is the marginal benefit of pollution and  $D'(M)$  is the marginal damage of pollution, then to maximise the net benefit of economic activity, the pollution flow,  $M$ , should be chosen so that

$$NB'(M) = B'(M) - D'(M) = 0, \quad NB''(M) < 0$$

or, equivalently, that

$$B'(M) = D'(M)$$

which means that the net benefits of pollution can be maximised only where the marginal benefits of pollution equal the marginal damage of pollution, as shown in Figure 7.

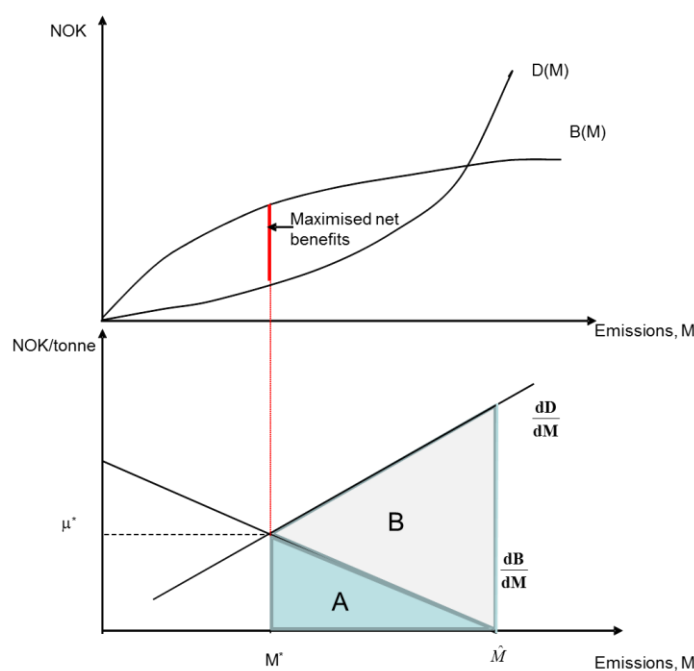


Figure 7. Total and marginal damage and benefit functions, and the efficient level of flow pollution emissions. Source: Perman et al. (2011).

The efficient level of pollution is  $M^*$  (Figure 7). If pollution is less than  $M^*$ , the marginal benefits of pollution are greater than the marginal damage from pollution, so higher pollution will yield additional net benefits. Alternatively, if pollution is greater than  $M^*$ , the marginal benefits of pollution are less than the marginal damage from pollution, so less pollution will yield more net benefits.

The value of marginal damage and marginal benefit functions at their intersection is labelled  $\mu^*$  in Figure 6. As there is no market for pollution,  $\mu^*$  is a hypothetical or shadow price of pollution. This price has a particular significance in terms of an efficient rate of emissions tax or subsidy.

Another interpretation of the emissions efficiency condition is demonstrated in Figure 8. The efficient level of pollution is the one that minimises the sum of total abatement costs plus total damage costs. Marginal benefit in the Figure 8 is relabelled as marginal abatement costs, which according to the concept of pollution benefit, described earlier, is an equivalent to it.

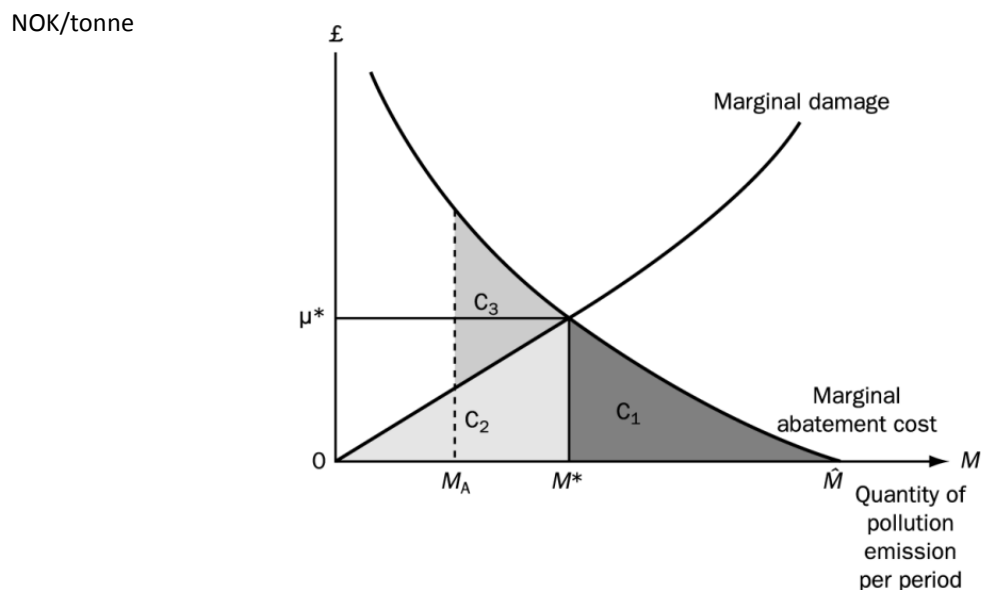


Figure 8. The economically efficient level of pollution. Source: Perman et al. (2011).

At the efficient pollution level  $M^*$ , the sum of total damage costs (the area  $C_2$ ) and total abatement costs (the area  $C_1$ ) is  $C_1 + C_2$ . Any other level of emissions yields higher total costs. For example, if too little pollution is produced (or too much abatement is undertaken) with a pollution flow restricted to  $M_A$ , it can be deduced that the total costs rise to  $C_1 + C_2 + C_3$ , so  $C_3$  is the efficiency loss arising from the excessive abatement.

As follows from the model, in order to define the efficient level of pollution, the regulator needs to have sufficient information about the location of the marginal damage and benefit function. The shape of the functions might be different from those assumed in the models above. Førsund and Strøm (2000) demonstrate a different location of the functions (Figure 9 a,b), that leads to other solutions for the optimum problem. Figure 9a shows the case where emissions under certain level  $M^*$  cause no damage to the environment. The pollution produced by the industry should not exceed this level, which is the efficient level of emissions in this case. The condition of achieving this

solution is that the marginal damage function starts from a positive value greater than the marginal cost function. The opposite situation is also possible, when the optimum is achieved at the initial level of emissions (Figure 9b).

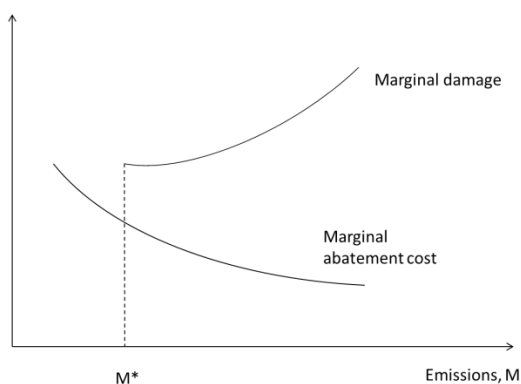


Figure 9a). Optimal solution with no damage

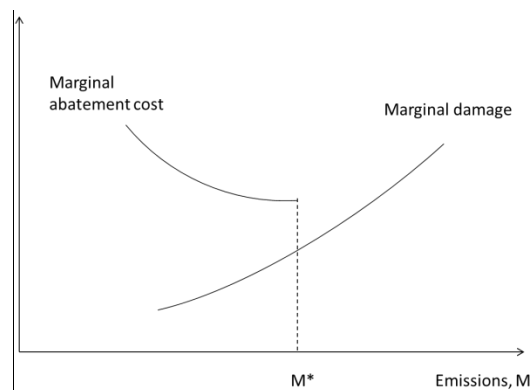


Figure 9b). Optimal solution with no abatement

Source: (Førsund & Strøm, 2000)

Helfand et al. (2003) outline conditions that influence the location of damage function. To find the economically efficient level of pollution  $M^*$  for regulation purposes, an aggregate damage function should be known. It represents damage to all affected individuals and is typically constructed by summing the effects of pollution across individuals. This aggregation process suffers from the same difficulties that any aggregation of individual preferences faces, such as whether to weight the preferences of all individuals the same, or whether a gain to one individual offsets a loss to another. A proper model of pollution should also include damage dependent upon environmental qualities and the ambient qualities of a pollutant, since the effect of the pollutant will vary across different environments. Effluent transport and special heterogeneity are also factors influencing the modelling of the damage function.

Actual determination of the damages associated with pollution typically involves at least two steps (Helfand et al., 2003). In the first step, the physical effects of pollution are identified, with reliance on the appropriate sciences. The second step is to assign a monetary value to these damages. Putting damages into monetary units is necessary for identifying the optimal level of pollution, since the damages are compared with abatement costs.

Different methods have been developed for the valuation of environmental services, such as contingent valuation, production function, hedonic price, travel costs, etc. (Hanley & Barbier, 2009).

The application of some valuation methods is often limited to specific types of ecological services. The production function method is used in pollution control cases. This approach, also called “valuing environment as an input” is similar to determining the additional value of a change in the supply of any factor input. If changes in the regulatory and habitat functions of ecosystems affect the marketed production activities of an economy, then the effects of these changes will be transmitted to individuals through the price systems via changes in the costs and prices of final goods and services. One should be aware of the limitations of these methods. As pointed out by Helfand et al. (2003), there is considerable controversy about the problem of monetizing damages associated with pollution caused by the technical, political and moral concerns of the approach.

Conversely, the problem of defining the abatement cost function is more straight-forward, because a market exists for input factors and the final goods of the production process. The methods for deriving economy-wide abatement cost functions are worked out for a number of pollutants. The methods that incorporate differences in abatement technologies will be discussed in Section 3.2.

### **Pollution control instruments**

Once the efficient level of emissions  $M^*$  has been defined, pollution control instruments can be enforced by the regulator in order to bring emissions to this level. There are a variety of instruments available to a regulator that can be used to achieve the target level of emissions. The choice of instruments will depend on the multiple objectives and is likely to involve trade-offs between alternative criteria such as cost-efficiency, long-term effects, information requirements and others.

Cost efficiency criterion has received the most attention in the environmental economics literature. According to Perman et al. (2011), if one particular instrument can attain the target at lower real cost than any other, then the instrument is cost-effective. Usually there will be many sources of an emission, and so many potential abaters. This raises the question of how the overall target should be shared among the sources. The least-cost theorem of pollution control provides an answer: a necessary condition for abatement at least cost is that the marginal cost of abatement be equalized over all abaters. This principle is demonstrated in Figure 10.

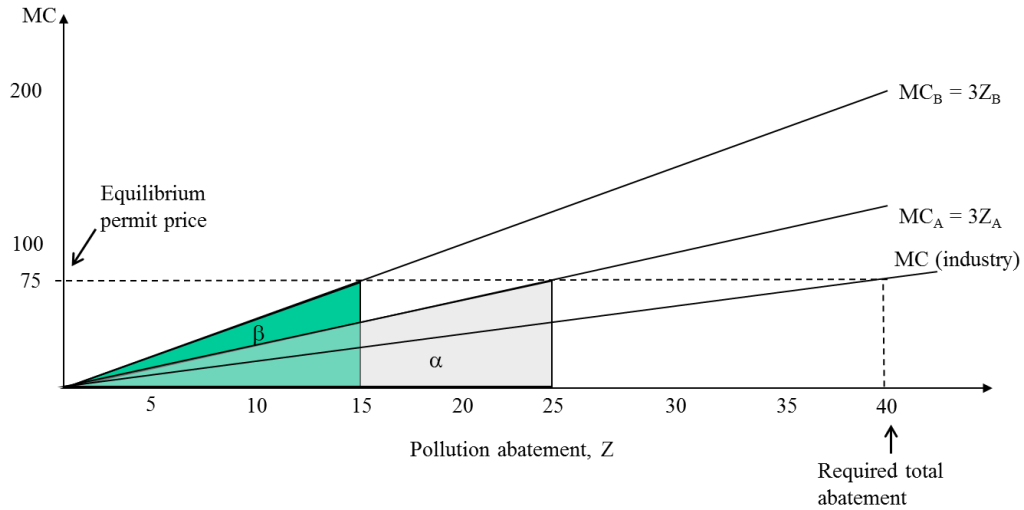


Figure 10. Example of marginal abatement cost functions for the two firms. Source: Perman et al. (2011).

In Figure 10, the two abatement cost functions of firms A and B are given:

$$C_A = 100 + 1.5Z_A^2 \quad \text{and}$$

$$C_B = 100 + 2.5Z_B^2$$

where  $Z_A$  and  $Z_B$  are the levels of pollution abatement giving the total abatement target  $Z = 40$ . The least-cost solution that satisfies the condition  $MC_A = MC_B$  gives the answer  $Z_A = 25$  and  $Z_B = 15$  in this numerical example. At those respective abatement levels both firms have marginal abatement costs of 75. The minimized total abatement cost here is 1700. Any other solution will result in higher total costs for the economy.

A least-cost solution will generally not involve equal abatement effort by all polluters. Where abatement costs differ, cost-efficiency implies that relatively low-cost abaters will undertake most of the total abatement effort, but not all of it.

Førsund and Strøm (2000) classify pollution control instruments as direct and indirect ones. Other authors also suggest an institutional approach (Perman et al., 2011) or non-regulatory instruments (Helfand et al., 2003) as another group. The latter seeks to improve existing social or institutional arrangements that facilitate environmental damage-reducing voluntary decentralised behaviour, and is not of particular interest in this study. The analysis is concerned with applying direct (also called “command-and-control”) instruments and indirect (market-based) instruments.

## Direct (command-and-control) instruments

Command-and-control is the dominant method of reducing pollution in most countries. One of the most common types of this method is *non- transferrable emissions licences*. The licences (permits or quotas) are created by the authority for the total allowable quantity of emissions and distributed among individual sources under certain criteria. The licences are non- transferable (they cannot be exchanged between firms), and therefore, each firm's initial allocation of pollution licences sets the maximum amount of emissions that is allowed. A licence scheme will have to be supported by monitoring and enforcement systems that prevent non-compliance. Under special conditions, the use of such emissions licences will achieve an overall target at least cost, but it is highly unlikely that these conditions will be satisfied, because the regulator usually does not possess information about each polluter's abatement cost function from which it could calculate the level of emissions for each firm. These controls will not usually be cost-efficient (Perman et al., 2011).

A regulator can also introduce *a minimum technology requirement*. These are regulations that specify the required characteristics of production processes or capital equipment used. Examples of this approach are known as the best practicable means (BPM) or best available technology (BAT). In some variants of this approach, specific techniques are mandated. These instruments are usually not cost-efficient because they do not focus abatement effort on polluters that can abate at least cost. Technology requirements restrict the set of choices allowed to firms to reduce emissions. Decisions about emissions reduction are centralized when they may be better left to the firms, as the firms would choose the method only if it is least-cost for them to do so (Perman et al., 2011). However, as noted by Førsund and Strøm (2000), the authority would usually set the overall target with regard to private costs and technical possibilities. If  $M_0$  is the uncontrolled level of emissions and  $M_{pract}$  is the practically achievable abatement in regards to cost, the target level of emissions  $M^*$  can be defined so that

$$\frac{M^*}{M_0} \leq \frac{M_0 - M_{pract}}{M_0}$$

In this case the target might not be the one economically efficient. Perman et al. (2011) conclude that although technology-based instruments may be lacking in cost-efficiency terms, they are sometimes capable of achieving large reductions in emissions quickly.

## Market-based instruments

Market-based (indirect) instruments work by altering the structure of the pay-offs that agents face by creating incentives for individuals or firms to voluntarily change their behaviour (Perman et al., 2011). The pay-off structures are altered by changing relative prices. Two common ways of doing this are:

1. By the imposition of taxes on polluting emissions, or by the payment of subsidies for emissions abatement;
2. Through the use of tradable emission permit system.

The mechanism for imposing tax on polluting emissions is demonstrated in Figure 11. To attain the efficient level of pollution, it is necessary to have solved the net benefit maximisation problem discussed above (Figure 7). A shadow price of emissions  $\mu^*$  is the rate at which the tax (or subsidy) should be applied per unit of emissions (abatement). The diagram uses aggregate, economy-wide marginal benefits and marginal damage functions.

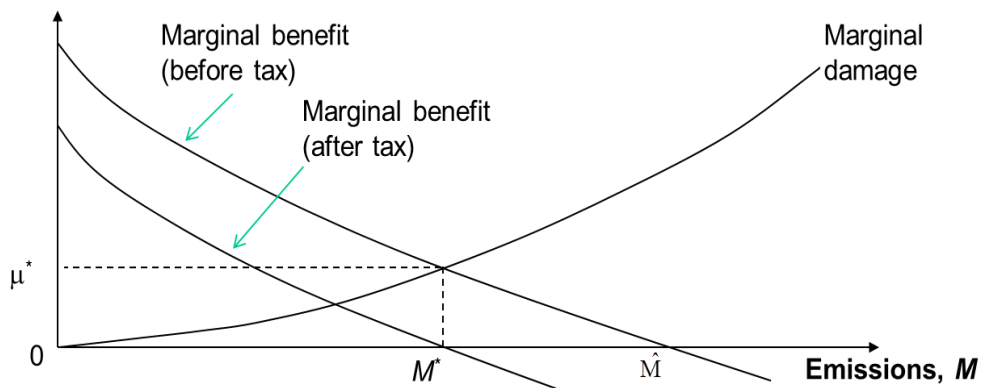


Figure 11. Economically efficient emission tax. Source: Perman et al. (2011).

In the absence of an emission tax, emissions will be produced to the point where the private marginal benefit of emissions is zero. This is shown as  $\hat{M}$ , the pre-tax level of emissions. An emissions tax is introduced at the constant rate  $\mu^*$  per unit emission, the value of marginal damage at the socially efficient pollution level. Once the tax is operative, profit-maximising behaviour by firms leads to a pollution choice of  $M^*$  (where the post-tax marginal net benefit of additional pollution is zero). Levying an emission tax at the rate  $\mu^*$  creates just the right amount of incentive to bring about the targeted efficient emission level,  $M^*$ . The tax eliminates the wedge (created by pollution

damage) between private and socially efficient prices. It brings private prices of emissions (zero, before the tax) into line with social prices. The tax will not only bring about a socially efficient aggregate level of pollution; it will also achieve that target in a cost-effective way. Under the tax regime all firms adjust their marginal abatement cost with the tax rate. As the tax rate is identical for all firms, so are their marginal costs.

As noted by Perman et al. (2011), knowledge of both the aggregate marginal pollution damage function and the aggregate emissions abatement cost function are necessary for achieving a socially efficient emission target at the least real resource cost to the economy as a whole, but it is not necessary to know each firm’s marginal abatement cost function. This result differs from the case of command-and-control instruments, where attaining an aggregate target at least real cost does need that additional and more demanding information.

An authority may not have sufficient information to define economically efficient level of emissions,  $M^*$  due to the difficulties of damages valuation described earlier. This might also be the case when the regulator wishes to set an overall emissions target on some other basis, such as health standards. In this case, the marginal damage function is being treated as irrelevant, and a target of emissions,  $\tilde{M}$  is being set exogenously (Figure 12).

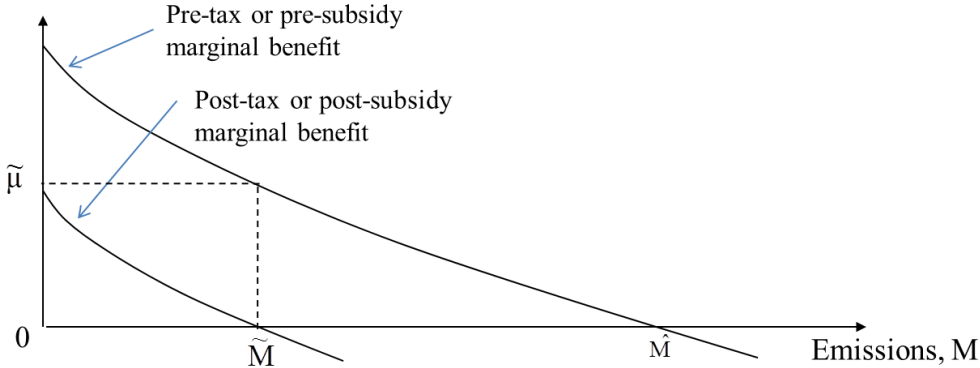


Figure 12. Emissions tax and abatement subsidy schemes when marginal damage is unknown, or when a target is being set on grounds other than economic efficiency. Source: Perman et al. (2011).

Figure 12 makes it clear that to attain this (or any other specific) emissions target using a tax or subsidy instrument, knowledge of the aggregated (pre-tax or pre-subsidy) marginal benefit of emissions function would be sufficient. For any target  $\tilde{M}$ , the location of that function allows identification of the tax rate  $\tilde{\mu}$  that would create the right incentive to bring about  $\tilde{M}$ . By



construction, the marginal net benefit of emissions is exactly equivalent to the marginal abatement cost function.

Even though the target is not a socially efficient one, the argument used earlier about cost-efficiency remains true here: the emission tax, levied at  $\tilde{\mu}$ , attains target  $\tilde{M}$  at least total cost, and so is cost-efficient. This result is particularly important for the problem studied. It suggests that to achieve any arbitrary aggregate target at least cost the authority does not need to know the aggregate marginal pollution damage function. Knowledge of the aggregate abatement cost function alone is sufficient for achieving the target at least cost. This means that even with insufficient information on the location of both functions, the regulation authority might still select some arbitrary positive level of emissions tax per unit emissions, knowing that some degree of reduction will be achieved (Perman et al., 2011).

Along with taxes (subsidies) tradable emission permits are used to achieve target level of pollution. The mechanism of this instrument can be demonstrated in Figure 10. In this numerical example used earlier, the uncontrolled emissions of firm A are 40 units, while firm B emits 50 units. If the target total level of emissions is 50 and distributed equally, the permits are traded between the two firms. Since firm A has lower abatement costs, it will sell permits, and firm B will buy at equilibrium price 75 NOK. At this price the total cost of abating 40 units is minimised. The equilibrium permit price is found as the industry marginal cost at the required level of total abatement.

So far in this section, flow-damage uniformly mixed pollution has been discussed. The target level of emissions for a stock damage pollutant with emissions distributed non-uniformly will differ between sources. The efficient ambient pollution level will also differ among receptors (individuals affected by pollution). Consequently, this type of externality requires different modelling and specific pollution control instruments. Zoning and other types of planning control form a substantial part of the long-term way of dealing with spatial aspects of pollution. Non-uniformly mixed emissions case will not be considered in the thesis. However, spatial distribution of pollutants and their accumulation in the environment are relevant issues for the problem studied, as will be showed in the following chapter. These aspects would need to be included in broader research.

The theoretical framework of the externality problem given in this section will be applied in the analysis of the salmon lice challenge in aquaculture in Chapter 4. The first two research questions of the thesis will be targeted. The salmon lice spread in the coastal waters will be seen as density-dependent pollution, produced by fish farms. Flow-damage, uniformly mixed pollution

model will be generally used for discussion. Available assessments of damage and abatement cost will be reviewed from the perspective of “production - production” and “production -consumption” cases. The current target level of emissions will be discussed in relation to the social optimum concept. The “green” licences initiative and current regulations will be analysed from the perspective of instrument classification and cost-efficiency criterion.

### **3.2 Abatement cost as a technology specific function**

This section provides a methodology for the empirical part of the study, which is a comparison of abatement costs in terms of different technologies.

Issues related to technological change are part of a discussion in environmental economics and policy. Jaffe, Newell, and Stavins (2003) point out the major influence the technologies have on the analysis of pollution control. For example, the uncertainty about the future rate and direction of technological change are often important factors in "baseline" forecasts of the severity of environmental problems and therefore, the evaluation of damages. An example supporting this statement is the report on the future development of Norwegian seafood industry (Olafsen, Winther, Olsen , & Skjermo, 2012), where salmon production is estimated to increase to 5 million tonnes, provided that major environmental issues such as salmon lice and fish escape are solved. In particular, it is assumed in the report that lice spread is under control by 2050 with the help of vaccines and other “biological and technological solutions”.

From a short-term perspective, the role of abatement technologies in forming the abatement cost function is underlined by a number of economists. Beaumont and Tinch (2004) suggest that abatement cost functions, that incorporate technological differences, can be used to provide an estimate of cost to reach a required level of abatement, and also to reveal the most efficient route to this discharge level.

According to the “win-win” concept by Porter (1991)it is essential that environmental management is based on an understanding of the technologies available and the associated costs, benefits and pressures involved when implementing waste reduction technologies.

In a more recent review, Kesicki and Strachan (2011) stressed out that technologically detailed marginal abatement cost curves can help in the context of research, development and deployment policies by providing insights into the marginal abatement cost of technologies and give an indication about the necessary level of fiscal incentives or tariffs. Concerning command-and-

control instruments, they agree that technology specific abatement cost functions give policy makers guidance on the maximum abatement potential.

Taking into consideration the theoretical aspects described, an assessment of abatement cost is performed in Chapter 5 in order to provide grounds for answering the third research question of the thesis. The discussion will focus on the influence of technology difference on defining abatement cost function location and, therefore, the target level of pollution.

## Data and model

The results of “green” licences allocation in regard to the abatement technologies choice are shown in the Table 2. Most of these abatement methods are currently under testing or recently implemented and a number of research projects are now focused on these techniques. By analysing their effectiveness and costs the economists acquire essential information that can contribute to modelling of the cost and benefits of externalities in the industry.

Table 2. Salmon lice abatement technologies approved in “green” licences allocation

| Salmon lice abatement technology/method      | Number of licences |         |         |
|--|--------------------|---------|---------|
|  | Group A            | Group B | Group C |
| Use of large smolt                           | 19                 | 1       | -       |
| Lice shielding skirt                         | 20                 | 4       | 6       |
| Cleaner fish (farmed lumpsucker)             | 18                 | 9       | 5       |
| Use of fish with enhanced resistance to lice | 15                 | -       | 2       |
| Further development of mechanical delousing  | 11                 | 2       | -       |
| Extended fallow periods                      | 2                  | -       | -       |
| “All inn – all out”                          | 4                  | -       | -       |
| Closed containment floating systems          | -                  | -       | 9       |
| Land-based production                        | -                  | -       | 1       |

Source: Furuset (2014d)

As seen from Table 2, the most commonly proposed methods in all groups were the lice shielding skirt and use of cleaner fish in the cages. Most of the applicants planned to introduce these two methods in combination at the “green” production site.

A concept dominating in Group “C” was production in closed containment floating systems instead of open cages. These semi-closed systems were given priority by the working group despite the fact that they were to be used only until the salmon are 0.4-1 kg. This concept is similar to production with large smolt, proposed by many firms in Group A. Only one company is going to use its “green” licence for closed land-based production.

In order to compare the costs of different methods the equal annual cost method will be applied. According to Ross, Westerfield, and Jordan (2003) the method can be used as a decision-making tool in capital budgeting when comparing the annual cost of assets with unequal service-lives and operating costs, for example in comparing technology options. A similar method is used by Beaumont and Tinch (2004) for building abatement cost curves. Their model will be used as a basis for the abatement alternatives assessment:

$$\text{Annual total cost} = \frac{r(1+r)^t}{(1+r)^t - 1} * \text{Investment cost} + \text{annual operating costs}$$

where  $r$  is the discount rate and  $t$  is the lifetime of the technology.

Apart from investment cost and operating cost for each type of abatement technique, the secondary effects of technology use should be included. These factors might be both positive (e.g. improved production efficiency) and negative (e.g. increased fish mortality), as will be demonstrated in Chapter 5.

The equation is transformed using the factor  $a(r, t)$  as shown in (Bye, 2014):

$$a(r, t) = \frac{r}{1 - (1+r)^{-t}}$$

The final model will take the following form:

$$\text{Annual total cost, NOK} = a(r, t) * \text{Investment cost} + \text{annual operating cost} + \text{secondary cost/benefit}$$

As seen in Table 2, only some of the technologies are exclusively targeting salmon lice abatement. Closed systems, for example, are an entirely new production method that is aimed at improving a number of parameters, including risk of fish escape and chemical pollution. The same applies to the general improvement of production routines such as the “all in – all out” principle or extended

fallow periods. The method of equal annual cost requires that costs be attributed to a particular type of abatement. Therefore, only methods specially developed to reduce sea lice levels are included in the assessment in Chapter 5. The only exception is the use of large smolt in production. The abatement effect of this method, both in terms of sea lice and fish escape, is not documented and therefore is considered to be minor in the assessment. Five abatement technologies are thus included in the comparative assessment:

1. Lice shielding skirt
2. Cleaner fish (farmed lumpsucker)
3. Use of large smolt
4. Use of fish with enhanced resistance to lice
5. Mechanical delousing

For other, more complex methods, the cost should be attributed to the cumulative abatement effect (escape risk reduction, lower sea lice levels and chemical-based pollution), which goes beyond the scope of this study. For the purposes of comparison an element representing such complex method will be added to the results.

In addition, cost of traditional bath treatment is included in the results in order to illustrate the effectiveness of new methods compared to the chemical delousing.

Another important limitation in the model used here is that the five techniques are assessed separately, without taking into account possible combinations and increased abatement effect of these combinations. A methodology for incorporating common combinations can potentially be worked out in further research.

The new methods of salmon lice reduction are not limited to those that appeared in the applications for green licences. According to the overview by Kvistad (2014), there is on-going research on other methods such as the development of vaccines, laser and electro-technologies, fresh-water delousing, special feed etc. Some methods, such as the off-shore salmon farm concept were not accepted as effective by the working group. Due to the limited scope of the study only five abatement techniques are discussed. Nevertheless, the method of equivalent annual costs can be applied for comparison with other abatement methods.

According to the model, total abatement cost comprises three elements. Investment cost is the initial cost of the equipment (such as lice shielding skirt) and installation. Operating cost include

estimation of additional labour force, materials, fish feed and energy specific for each technology. Other costs may be associated with the possible negative influence on fish growth that particular technology can impose. On the other hand, an abatement technique can have a positive secondary effect, enhancing production conditions. Since the techniques listed in Table 2 are new to the industry, the data on all three elements is limited. Available data from research reports and other public sources will be gathered. As for the missing data, a sensitivity analysis is performed to highlight the contribution of the operating cost to the result.

The discount rate chosen is 4%, as recommended by the Economic Policy Department (2014) for public project assessment. It is important to note that for some of the abatement methods chosen for this study the discount rate will be influential due to large and long-term investments in equipment, while for using cleaner fish or purchasing lice-resistant smolt, the discount rate is not that important. The sensitivity of the model regarding discount rate will also be assessed.

Eschenbach and Smith (1992) performed sensitivity analysis for the equivalent annual cost method, considering different parameters such as premature project terminations, subsequent cost changes, discount rates, amount and profile of annual costs. They concluded that the robustness of the method is strong in “typical applications”.

The cost assessment role in this study is to demonstrate the differences in abatement costs for different technologies in order to support reasoning in the discussion of theoretical aspects. Thus, only approximate estimates are made using the available data. A more precise assessment can be made as part of microeconomic research with more advanced methods incorporating biological sub-models such as the salmon growth model.

## Chapter 4: Salmon lice as an externality problem

### 4.1 Salmon lice as pollution

Before the discussion of possible pollution control instruments for the salmon lice problem in the framework of externality theory, it is necessary to demonstrate that salmon lice can be seen as a pollutant from both a physical and economic perspective.

In environmental economics literature the concept of externalities is traditionally applied to chemical pollutants such as carbon dioxide, nitrogen oxide, heavy metals and organic waste. These pollutants are unavoidable as a part of input in production process. Salmon lice emission has a different physical nature and can be seen as biological pollution. The term ‘biological pollution’ can be found in literature regarding the adverse effects of invasive species in the marine environment (e.g. Horan, Perrings, Lupi, & Bulte, 2002; Olenin et al., 2011). Biological pollution is defined by Olenin et al. (2011, p. 2599) as

“...the adverse impacts of invasive alien species at the level that disturb ecological quality by effects on one or more levels of biological organisation: an individual (such as internal biological pollution by parasites or pathogens), a population (by genetic change, e.g. hybridization), a community (by a structural shift), a habitat (by modification of physical–chemical conditions), or/and an ecosystem (by alteration of energy and organic material flow)”.

Elliott (2003) draws a parallel between the physical characteristics of chemical-based and biological pollutants, such as accumulation and degradation in the environment, harmful effects, chronic and episodic emissions etc., and shows that they are all attributed to unwanted distribution of organisms and chemicals. Risk assessment and management concepts are usually used in this kind of research.

Salmon lice, even though not an alien species, can be treated as biological pollution following this concept. However, instead of a risk assessment approach, modelling of the actual damage and abatement cost is discussed in this study. In this respect it is important to show that *L. salmonis* in salmon aquaculture has even more physical characteristics in common with chemical pollution, compared with invasive species.

As noted in the previous chapter, the unavoidable character of pollutants is explained by the use of materials as input leading to discharge of waste (Helfand et al., 2003). Although salmon lice is not an input of the fish farming production process, the parasite is being “produced” at farms due

to the high density of hosts, and is released as emissions into the environment in the same way as chemical-based pollutant.

Research into the production of lice began on a broad scale in 1990s when an infestation of early returning trout was registered in several regions with high fish farming activity. Costelloe et al. (1998) investigated the dispersion of salmon lice larvae from a single cage and a farm system in Ireland. The results showed that the highest density of larvae is found inside the cage and in close proximity (within 10 m) to it. However, the larvae, as well as nauplii and copepodid, were found as far as 2 km from the farm system.

According to Asplin et al. (2014) sea lice can move in the water column at more than 2 km/h for distances up to 100 km. With lower temperatures the spreading potential increase. The reason for this is that larvae are developing more slowly.

The relationship between production scale and abundance of *L. salmonis* was later modelled in a number of studies using various methods. Based on a simple production model of salmon lice, Heuch and Mo (2001) showed that the infection pressure is the product of the number of fish in the system, and the number of lice per fish. They demonstrated that the production of lice and their larvae in an aquaculture system is much higher than in wild salmon populations due to the much larger number of farmed than wild salmonids.

Jansen et al. (2012) investigated the effect of farmed fish densities on parasite abundances and control efforts in the Norwegian fish farming system. They analysed the empirical data statistically and came to a similar conclusion, namely that a large population of hosts is likely to harbour a large population of adult parasites and thereby produce more infective larvae than a smaller population of hosts. In other words, emission (waste) in the form of lice depends on the input of fish (“material”) in production. However, this relationship is most likely not linear. Stormoen, Skjerve, and Aunsmo (2013) found with the help of a stochastic simulation model that the number of lice in a cage increases slowly until the amount of lice becomes large enough for massive lice propagation to take place, where all females will successfully reproduce. Their model and empirical findings suggested exponential growth in lice production.

Infectious larvae densities are also likely to be affected by temperature, since both the fecundity and generation time of sea lice are temperature dependent (Boxaspen, 2006). The emission rate will thus be determined by the production conditions, which is also true for chemical-based effluents.



Since the salmon louse is a living organism integrated in the ecosystem, its epidemiology, along with environmental qualities, determine whether it is considered as flow-damage or stock-damage pollution. The increase of infestation pressure on wild salmonids has been registered and its connection to farming is well documented, so it may be reasonable to assume the increase of sea lice “stock” in the surrounding waters as a result of salmon farming. This means that the biological pollutant accumulates in the environment at least in the short-term, and therefore, initial pollution levels representing stable and unstable equilibriums, exist. However, considering the lifecycle of the salmon louse, it seems unlikely that its increasing stock in the ecosystem would ever reach the unstable equilibrium point ( $X_H$  on Figure 6). Indeed, the copepodid, which is a planktonic infectious stage of sea lice larvae, depends on yolk reserves to supply their energy needs until it finds a suitable host. This gives them a finite life span, about five days, depending on temperature (Brooks, 2005). Such a short life span and the much lower density of wild salmonids suggest that only a small proportion of copepodids would attach to wild hosts. Moreover, infected smolts tend to return to fresh water where salmon lice do not survive, which increases the mortality of accumulated lice. Therefore, a high assimilation capacity of the environment can be assumed even at high emission levels. Supposing theoretically a removal of all salmon farms, the damage from accumulated lice will most likely have an effect on wild fish for only a short period of time. Following these considerations, salmon lice can be modelled as flow-damage pollution.

Another physical attribute of pollution which is relevant for parasite dispersion is the dependence of damages on the location of the emission source. The effect on wild stocks will depend on the proximity of the production site to salmon rivers and the migration routes of wild salmonids, especially smolt migrating to the sea. As shown in the review of externalities in Chapter 2, the infestation risk to out-migrating salmon smolt passing farm locations has been reported in different studies (e.g., Finstad et al., 2010, Bjørn et al., 2002). These reports not only confirm the production of lice by farms but highlight the importance of the farm location.

Economically, salmon lice emission is an externality problem, because it is costly to avoid. It is technically possible to have salmon production that would exclude the parasitic infection of farmed fish, and therefore, no lice would be emitted to the environment. Before the “green” licences initiative, the only commercially tested possibility for lice-free production was farming in closed land-based facilities. The cost of building and operating such farms is prohibitive. Estimates suggest that a land-based farm requires 200 times as much investment per unit capacity as traditional open

sea-cage technology (Furuset, 2014e). As seen from Table 2, only one applicant for a “green” licence proposed land-based production.

## **4.2 Damage and benefits of salmon lice pollution**

Salmon lice pollution demonstrates all the attributes of externality listed in the definition by Perman et al. (2011). The sea lice are produced by farms unintended, and there is no compensation made for damage caused by increased infestation pressure in the environment. It is important to distinguish several types of damage in the case of salmon lice originating from farms.

Firstly, as shown earlier, the populations of wild salmonids are affected, which has been proved by extensive biological research in Norway . The damages at stock-level include lice-induced mortality resulting in a lower number of fish returning to rivers. According to the externality theory discussed in the previous chapter, this is a case of “production-consumption” externality. Salmon rivers are a public good, and when polluted with parasite, many individuals who use a river’s environmental services, are affected. The cost of this damage is not met by the polluters, so that there is no compensation paid.

Secondly, the decline of local wild stocks not only threatens biodiversity, but might also cause economic losses if these stocks are exploited commercially. This is a “production-production” type of externality.

As the density of farms in some of the regions is quite high, there is a transfer of salmon lice between the farms. According to Aldrin, Storvik, Kristoffersen, and Jansen (2013), the transmission of lice from neighbouring farms causes 28% of infestation. There is thus a “production- production” case of externality as well. However, same report shows that 66% of lice in cages originate from inside farms due to the high density and number of hosts, which is another type of damage. This means that only a part of the private cost of lice at a farm is attributed to “production-production” externality, while the rest of damage is internalised.

The cost of lice for the industry, regardless of the origin of the parasite, includes increased mortality, reduced fish quality at slaughter, increased production costs per kilogram, and reduced growth performance and food conversion (Hamza, Rich, & Wheat, 2014). Costello (2009) also noted the effect on public perceptions of aquaculture as causing damage. According to Jansen et al. (2012), efforts to control infections in open cage systems are likely to surpass economically

sustainable levels at some host density. Sea lice, therefore, represent a potential density-dependent negative feedback mechanism that may limit growth in salmonid farming in Norway.

If the need for intervention is obvious in the case of “production-consumption” externality, the cost of damage at the farm-level can in theory be minimised by private bargaining. In practice, however, this is rarely achievable. Agreed actions against sea lice such as coordinated treatments and zoning have been enforced by authorities rather than private negotiations. The number of production units also prevents negotiating solutions that would minimise total abatement cost. The assumptions of the Coase theorem about full information on each other’s costs and zero transaction costs are thus not satisfied. An intervention is then also needed in the case of “production-production” externality.

Since all types of damage noted above are caused by the same pollutant, it might be assumed that by addressing the problem of environmental damage, private damages will be also reduced. A target level of pollution which is favourable for the environment, will also be effective in terms of reducing the private cost of lice. If the regulator is able to achieve optimal level of sea lice emission via available control instruments, this level would probably ensure the solution for both “production-production” externality and the internal cost problem. In order to find the target level of pollution and provide an assessment of compensation for externalities, the damage function should be defined based on an estimation of damages for the environment. Further, the abatement cost function should also be located.

The abatement cost in the case of salmon lice is associated with investment in cleaner technologies. Strictly speaking, abatement cost might include a reduction of output (fewer fish in cages will produce fewer lice), but in the aquaculture industry this possibility is not discussed. On the contrary, as follows from the previous discussion, growth in output is desired. The abatement cost function will thus be aggregated from the private cost of investment in the new abatement methods of all producers. Taking into account the private cost of lice discussed earlier, the following conclusion can be drawn. The benefit of pollution is diminished by the internal cost of lice control. Consequently, abatement costs will be lower, since internal damage is avoided, as shown in Figure 13.

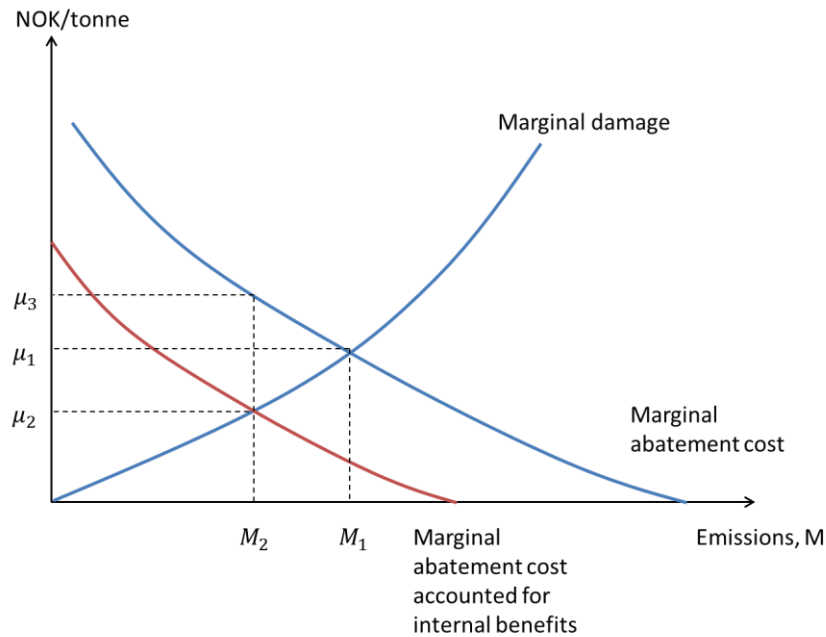


Figure 13. Marginal abatement costs accounted for internal cost of lice

On the figure, the difference in abatement costs is equal  $(\mu_3 - \mu_2)$ . The new efficient level of emissions,  $M_2 < M_1$  is achieved at a lower shadow price. Investment in cleaner technologies and production methods, therefore, will be beneficial for both society and the producers themselves.

### Damage function

The first challenge in the process of environmental damage valuation is quantifying the effects of pollution, such as stock decline due to lice-induced mortality. As described in Anon. (2012), there are methodological challenges that make it difficult to precisely estimate the number of fish lost due to lice infection. For example, stock-effect assessments are based on field data that is a source of uncertainty. The methodology proposed in the report relies on smolt infestation indicators (Table 3) and can only be used in the analysis of short-term effects. For estimations of stock development in the long term, historical data from field research is needed. These indicators can, however, be used in the bio-economic modelling of sea lice influence on wild stocks. The challenge of using these indicators for management purposes is that values are given for wild smolt and are not converted to values for the concentration of lice in aquaculture.

Table 3. Indicators for lice-induced mortality estimation in salmon populations

| Infestation pressure based on field samples, lice/gram biomass of smolt <sup>3</sup> | Extra mortality due to sea lice, % |
|--|------------------------------------|
| 0-0.1  | 0                                  |
| 0.1-0.2  | 20%                                |
| 0.2-0.3  | 50%                                |
| >0.3   | 100%                               |

Source: Anon. (2012)

Attributing a monetary value to such damages is another challenge. As discussed in Chapter 3, such valuation is associated with putting a price on various environmental services that are provided by the wild stock of salmonids. Meeren (2013) defines three groups of services that society receives from wild salmon:

1. Production services (recreational and commercial fishery, genetic resources)
2. Culture-based services (symbolic value, recreation, importance for science and education)
3. Ecosystem regulation services (nutrition value, food chain balance, biodiversity and habitat)

The importance of these services is recognised in the Norwegian legislation (e.g. Lakse-og innlandsfiskloven, 2009; Naturmangfoldloven, 2009). As noted earlier, existing valuation methods are determined for specific services and do not include all of them in the price of a particular environmental asset. It is important that the regulator defines the kind of environmental services that are to be evaluated and protected. One of the requirements of the industry regarding new environmental strategies for aquaculture was to specify which wild stock were a priority for the state (NSL, 2014). The argument against stricter limits of sea lice emission, expressed during public hearings, was that 0.5 lice per fish has long been a limit that ensured no harm to the wild Atlantic salmon, while 0.1 lice per fish limit seems to be designed for the protection of wild trout. Trout,

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<sup>3</sup> No differentiation between male and female lice is made in this system. Total number of lice of all stages are counted.

according to NSL (2014) was never been the target species for protection regulations including the establishment of national salmon fjords.

There have been a few studies in recent years that aimed to provide framework for incorporating the biological influence of salmon lice in the economic valuation of damages. A bio-economic model proposed by Liu, Sumaila, and Volpe (2011) uses a salmon population assessment method, adding an economic element to the age-structured model. The economic influence of juvenile's salmon mortality is associated with lost profits in the fishing industry that exploits wild salmon resources. The findings indicated significant economic loss with mortality greater than 20%. It was stressed, however, that the market price of salmon has a substantial influence on effort and profit. Since the wild stock of salmon was treated as an input in production, this method demonstrates the use of production function approach to valuation of environmental services.

### **Abatement cost function**

As concluded earlier, abatement cost function will be defined by investment in abatement methods and the private cost of lice. The first element is discussed in the following chapter, while in this section lice-induced damages on farm-level are examined.

According to the report by Salmar (Furuset, 2014c), the company spent 0.95 NOK per kg of fish produced on sea lice control. Marine Harvest reported the cost of lice as up to 2.45 NOK per kg salmon produced on one of the production sites in 2013 (P. M. Jensen, 2013). The costs included the use of cleaner fish, special feed and chemical treatment. The producer calculated the direct cost of lice at 1 367 000 NOK per production unit (sea cage 157 m). Nationwide, the costs of lice are estimated around 2 billion NOK with average direct costs 1-2 NOK/kg (Sandvik, 2014). Table 4 shows the structure of costs in Norwegian salmon aquaculture. As seen from the table, the expenses for lice control 1-2 NOK/kg are comparable to those for salary and smolt purchase value.

Table 4. Average costs per kg production in Norwegian aquaculture industry

| Cost components                        | Average cost per kg production in 2013, NOK |
|--|---|
| Smolt                                  | 2.19  |
| Feed                                   | 11.50                                       |
| Insurance                              | 0.11  |
| Salary                                 | 1.8   |
| Depreciation                           | 1.23  |
| Other production costs                 | 5.58  |
| Capital cost                           | 0.28  |
| <b>Total production cost</b>           | <b>22.69</b>                                |
| Processing                             | 2.64  |
| <b>Total cost including processing</b> | <b>25.33</b>                                |

Source: Directorate of Fisheries (2014a)

Concluding discussion of the damage and cost functions, some arguments about the shape of the curves should be noted. It is difficult to define whether the shape of the marginal damage and abatement cost curves will be like those demonstrated in Figures 8 and 9, but it is unlikely that a “no damage” solution demonstrated in Figure 9a) is applicable. Assuming natural assimilation capacity as proposed in (Anon., 2012), the total damage is equal to zero if the sea lice level at wild smolt is lower than 0.1 lice per gram biomass. This means that the target level of emissions might be low so that it is barely achievable at low cost for producers. It is possible, that the shapes of the marginal curves are close to those sketched in Figure 9b), where the maximum unregulated level of emissions is the social optimum. In this case, the total abatement cost for any lower emissions will be higher than total damage.

## Target level of salmon lice pollution

Due to the difficulties in defining location for marginal damage and abatement cost functions, this method has not been used in the calculation of the efficient level of sea lice emission. There were attempts to calculate the number of lice in an ecosystem based on the biological sustainability principle. The model used by Heuch and Mo (2001) shows that as production rises louse limits must be lowered to keep the total egg production constant. According to the model (which is based on a number of assumptions) in 2000 the lice limit should have been 0.6 adult female lice per fish, which is close to the official limit imposed in February that year.<sup>4</sup> To stabilise lice spread in the growing production, this limit should have been lowered to 0.4 lice/fish in 2004. Sea lice thresholds shown in the Table 3 are also defined based on biological sustainability limits. However, they are determined for the purpose of monitoring wild stocks and the system does not suggest corresponding limits for farmed fish.

Sea lice limits for aquaculture imposed by authorities also take into account the biological effect, however, economic sustainability seems to be dominant principle for such regulations. Lice monitoring thresholds were first implemented in 1998, establishing a maximum level for sea lice per fish above which treatments must be implemented. Initially, these levels were set at a mean of two adult female lice per fish in spring, increasing to a mean of five adult female lice per fish in summer and autumn. These regulations were updated in 2000, and established a maximum limit of 0.5 lice/fish or four mobile lice in total for the period from December to June. A later update of regulations in 2009 included a limit of 0.5 lice/fish or three motile lice on average per fish from January 1 to August 31 of each year, and one adult female or five motile lice on average from September 1 to December 31 of each year (Hamza et al., 2014). There is no biological background given for these indicators in the regulations. The reasoning behind the target level is most likely a trade-off between the biological and economic sustainability, where authorities decide what emission level is practically achievable in terms of private costs, as discussed in Chapter 3.

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<sup>4</sup> From here and under the average number of female adult lice per farmed fish is given as “lice/fish”.



### **4.3 Instruments for achieving a salmon lice pollution target**

According to Perman et al. (2011), if market-based instruments are used, a target level of pollution can be achieved at least cost even if it is defined on grounds other than economic efficiency. Current regulations for sea lice control in Norwegian aquaculture, and those recently proposed, are mainly the command-and-control type.

#### **Regulations on measures against salmon lice, 2012**

The regulations on measures against sea lice in aquaculture (Forskrift om lakselusbekjempelse, 2012) include the limits for sea lice levels – 0.5 lice/fish - and prescribe the routine for lice counting on production sites and reporting to the Food Safety Authority. A coordinated plan for measures against sea lice is required within defined geographic zones. Where the plan is not sufficient, authorities can introduce zones where special measures are to be taken. These measures might include other limit indicators for sea lice and the reduction of biomass in cages. Coordinated seasonal treatments are established via the regulations in some counties.

This is a typical command-and-control approach, described in the previous chapter, where the target level of emissions is achieved by direct measures. The methods for keeping sea lice spread under control are not determined by the regulations, but the choice of effective methods is still limited to some extent by enforcing a coordinated time for treatment and zoning. As discussed earlier such instruments are effective in terms of emission reduction in a short time but they are not economically optimal, since they do not provide economic incentives for abatement. The success of the regulations is also questioned regarding parasite infection control. Chapter 2 discussed how the lice have become a limiting factor for production despite the current measures. Even though the average sea lice level was held at under 0.5 for the last three years (Figure 4), the need for new measures is admitted by authorities. The issuing of 45 “green” licences was an attempt to determine such new instruments.

#### **“Green” licences**

Distribution of aquaculture licences based on the environmental principle can be seen as a market-based instrument for pollution control. The economic incentives are provided to applicants in the form of future benefits from increased production. Producers are thus interested in effective abatement through innovation. The benefit can be seen as a subsidy which is paid to the abaters in the form of increased production capacity. The value of the subsidy in this case was reduced by the

price paid for the licence, but in the long term it might still be a positive value. Nevertheless, there are two major aspects of the “green” licences initiative that mean it cannot be classified it as an indirect, market-based measure.

First of all, the marginal abatement costs were not equalized among the participants as was demonstrated in Figure 10. Indeed, the applicants paid different prices for licence due to the auction-based distribution in Group B. As already noted, the ordinary price was 10 million NOK, while the highest auction bid was 66 million NOK. The abatement level was also different: 0.25 lice/fish were required in Groups A and B, while 0.1 lice/fish limit was required in Group C (Table 1). Since the initial level of abatement is different among producers, the value of benefit per unit abatement (accounted for the price of the licence) was also different. In a case of a purely market-based regulations an equal price for an equal unit of pollution (abatement) is paid (subsidized) for all firms.

Secondly, the maximum pollution limit was still defined by the regulations, which is an attribute of command-and-control instruments. For indirect measures the target level of pollution is achieved through taxes or subsidies, and is not enforced as mandatory. “Green” licences are thus another case of command-and-control measures.

### **Five percent growth proposal**

Shortly after the “green” licences regulation a new proposal for production growth was initiated by the government. According to the regulation draft (Ministry of Trade, Industry and Fisheries, 2014) , an increase of biomass by 5% at the price of 1.5 million NOK was to be offered to all producers based on their existing licences in 2015. Firms willing to expand capacity would have to ensure sea lice infection level under 0.1 lice/fish at any time of production. A system of sanctions presented in the document includes fines and eventually withdrawal of the given 5% capacity permit in cases of repeated violation of the requirement.

Similar to “green” licences regulations, this system has an element of market-based approach, since the producers are offered some benefit for their abatement effort. This instrument suggests equalised benefit for all producers, but again, the initial level of emission is supposed to be different, and so producers will abate unequal units to achieve the level of 0.1 lice/fish. Marginal abatement costs are therefore not equal as in an optimal pollution tax (abatement subsidy) system. The emission limit is also set on a mandatory basis, which identifies this proposal as a direct instrument.

## **New policy – “traffic light” system**

The allocation round of 2013 and the proposal for 5% growth are instruments that provide a temporary solution to the environmental problem. Last year the Ministry of Trade, Industry and Fisheries started the work on a new White Paper for growth in the aquaculture sector that would establish a long-term strategy and mechanisms for production growth. Three alternative principles are presented for public discussion (Aspaker, 2014):

1. Growth based on licence allocation rounds, as before
2. Annual increase in production according to a certain percentage
3. Zoning principle, when a decision on growth in a particular production area is dependent on its environmental status.

The first alternative suggests no change in the regulations. According to current legislation the state decides when, how and how much growth in salmon aquaculture should be allowed. This approach was criticised by aquaculture producers for the lack of predictability. Every new allocation was built on different criteria and did not provide equal opportunities for all firms. Subjectivity became a big issue especially after the “green” concessions allocation.

The second alternative is equivalent to the proposal of 5% growth described above. The environmental issues would then require special regulations. As established here, both principles are of the command-and-control type.

The third alternative for growth is based on zonation, where the spread of sea lice is seen as the main indicator of environmental status for different production zones. The “traffic lights” rule means that the environmental status of an area – “green”, “yellow” or “red”- would result in permission for growth, no change in production capacity or a reduction in biomass in the area, respectively.

As discussed earlier in this chapter, infection pressure, and therefore, environmental damage, depends on the location of emission sources and recipients relative to each other. Zonation takes this aspect into account. Non-uniformly mixed pollution cases require the calculation of an efficient level of emission for each source (Perman et al., 2011). The major challenge of the third proposal is thus to define indicators upon which a “green light” for biomass increase will be given in a particular zone.

Even though this rule changes the view on pollution forms, this instrument is still of a direct type, with no economic motivation provided for aquaculture companies.

## **Indirect regulations in salmon lice control**

When it comes to biological pollutants, market-based control instruments have not been implemented in Norwegian aquaculture so far. However, proposals for regulations based on a tradable permits system were discussed. Salmon Group (Kråkås, 2015) suggests that a system of tradable maximum biomass (MTB) should be introduced. In such a system producers experiencing large sea lice infestation pressure will not have to face losses associated with the reduction of biomass in cages. Instead, other production sites, with better control over sea lice, would be able to take over a permit for more biomass in production. Today's regulations set a maximum biomass limit, which should be followed at any time, regardless of season and sea lice levels. With tradable MTB a more flexible production could be achieved, according to Salmon Group. If the exchange of MTB is connected to sea lice level, such a system would function as shown in Figure 10, where the most effective firms make a larger abatement effort.

There were no suggestions for the introduction of a tax system in connection with the new policy. In the framework of externality theory, any target level of sea lice emission can be achieved through tax on emission unit, as shown in Figure 12. One of the challenges here is defining a unit of sea lice pollution. Environmental regulations today use the average number of lice per fish as an indicator. One way of defining tax value could be to calculate it per 0.1 lice/fish over the limit. Another challenge in tax or subsidy introduction is enforcement and control mechanisms. Fines associated with environmental damage will, as a rule, motivate underreporting. This can be demonstrated by Figure 5. As soon as the fines were introduced for escaped fish in 2007, the number of reported escapees dropped significantly. As noted in Chapter 2, this was probably a result of the technical measures taken in this period, but underreporting due to monetary sanctions cannot be excluded.

In terms of avoiding problems with compliance, a subsidy scheme instead of tax on lice may be a better option. According to the model (Figure 11) the mechanism of subsidy is similar to tax. The motivation, however, is different.

According to the model of pollution tax (subsidy), where the target level of emission is defined on grounds other than economic efficiency (Figure 12), the damage function can be treated as irrelevant. In this case, knowing the location of the aggregated abatement cost function is sufficient for calculation of the tax (subsidy). This model is applicable to the case of salmon lice pollution, where the target level of emission (e.g. 0.5 or 0.1 lice/fish) is not explained by the social optimum principle or biological reasons. The damage function, as was established earlier in this

chapter, is difficult to locate due to challenges of environmental services valuation. It is thus possible to focus on abatement cost function to calculate the tax which would move the pollution level to any arbitrary chosen point. It has also been shown that through taxation (subsidy) this level of pollution would be achieved at least cost.

One of the main points of discussion in this thesis is that technology choice has a great influence on abatement costs. In order to locate the abatement cost curve, technological development should thus be considered. Different abatement methods and techniques will have different costs. In this sense, the “green” licences regulations played a big role in the environmental management of Norwegian aquaculture. The application process and its results (Table 2) demonstrated the difference in current abatement techniques. If the aggregated abatement cost function is to be calculated for salmon lice pollution, all these alternative technologies should be examined. In the next chapter some of these technologies will be discussed. The difference in the abatement costs between them will be assessed following the methods given in Chapter 3.

## Chapter 5: Cost of sea lice abatement

### 5.1 Abatement technologies used on “green” farms

In this section cost model elements are described for each abatement method. These include investment period and cost, factors affecting operating cost and the secondary effects of the technologies. The ability to prevent or reduce sea lice infection is another key factor through which the methods are compared.

#### Lice shielding skirt

This technology works by preventing physical contact with lice. The salmon lice copepodites are typically found in the upper water column. Hevrøy, Boxaspen, Oppedal, Taranger, and Holm (2003) found that salmon held at 0-4 m depth developed higher infestation than salmon held at 4-8 m and 8-12 m depth. The hypothesis was then that putting a tarpaulin around the upper few meters of a sea cage (a skirt) will block the surface water from entering, and therefore infestation will be reduced (Stien et al., 2012). Figure 14 demonstrates the basic construction of such coverage.

Lice shielding skirts of various configurations made by different producers have been tested in recent years and are available on the market. Among these are a skirts produced by Calanus AS (luseskjørt) and by Botngaard AS (permaskjørt).

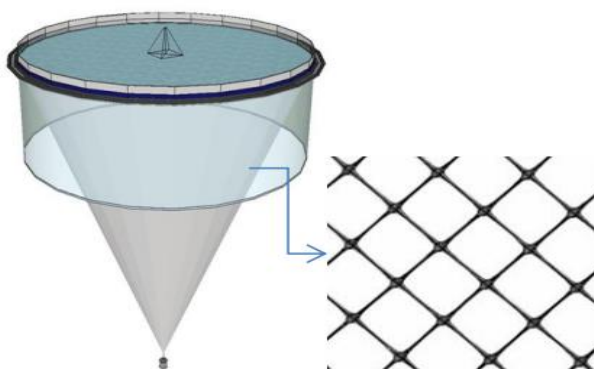


Figure 14. Lice shielding skirt. Source: Calanus.no

The results of recent trials of skirts produced by Calanus AS show that by using either 6 or 10 meter deep plankton nets, infestations of copepodites were significantly reduced. The greatest reduction was seen using 10 meter deep skirts (Næs, Grøntvedt, Kristoffersen, & Johansen, 2014). A report from the producer (Calanus AS, 2013) suggests that with long-term use of the skirt a level of salmon lice under 0.1 lice/fish is achievable. A significant reduction of infestation pressure (18% on average) was also reported for the construction by Botngaard AS. The abatement effect reached 54% if the skirt was installed on all cages at the production site (Lien, Stien, Grøntvedt, & Frank, 2015).

Investment costs for the equipment will depend on a number of factors, such as size, configuration of the skirt and transport cost. In 2013 the price of a 10x112 m skirt by Calanus AS was 213 000 NOK (Berg, 2014). Transport to the farm location and installation of the net was additional. The functional life of the skirt is 2-4 years, which means that the discount rate will have a significant effect on the calculation of annual costs.

An increase in operating costs is associated with cleaning the plankton net, its disinfection and reparation. These costs can be calculated from an assessment of working hours needed for the operations. There are other potential costs resulting from the use of lice shielding net. Stien et al. (2012) concluded from a pilot study that putting coverage around a full scale commercial sea cage may seriously decrease the oxygen saturation level available for the fish inside the skirt. Reduced water exchange and oxygen levels have also been noted in the recent report on the permanent lice shielding skirt (Lien et al., 2015). This means that operating costs might include oxygenation measures ensuring optimal conditions for growth. Otherwise, a production loss might be expected in the form of lower growth or increased mortality of fish. This loss can be calculated with the help of a biological sub-model.

### **Use of cleaner fish (farmed lumpfish)**

Cleaner fish species are used as a biological method of sea lice control in aquaculture. The Ballan wrasse (*Labrus bergylta*) is the biggest and most robust of the available wrasse species and has the greatest potential for large-scale biological delousing, particularly for use on large production sites. However, the wrasse species are temperature sensitive, making them unfit for use at low temperatures of less than 6 °C. As a cold-water alternative, the common lumpfish or lumpsucker (*Cyclopterus lumpus*) has been suggested (Imsland et al., 2014). Almost all applicants who proposed the cleaner fish method under the “green” licences allocation planned to use *C. lumpus* in the cages.

A reduction in lice level is achieved because lumpfish are effectively grazing on the parasite. The reported abatement effect with the use of lumpfish varies among different experiments. Imsland et al. (2014) reported a 58% reduction of adult male lice after 54 days of lumpfish placement in the cage; the number of adult female lice was 93% less than in the control group. The level of female adults was held at under 0.1 in cages with lumpfish, whereas the level in the control group had risen to 1.0, surpassing the threshold. According to FHF (2014) there is no data so far on the lice removal effect of lumpfish in full scale commercial use.

The investment cost for this method will be distributed over approximately 14-16 months, as this is the period of growth for lumpfish after which they are no longer useful in cages. This means that lumpfish is used for the entire period of salmon grow-out stage in sea water (Imsland et al., 2014). The price of lumpfish is currently around 15 NOK per fish including delivery (Nordbøe, 2014). With stocking density 10-15% in a cage with 200,000 salmon individuals it will account for 300,000 – 450,000 NOK per cage.

The loss of lumpfish is a major problem in the method. According to a report by Norwegian Veterinary Institute (A. Nilsen, Viljugrein, Røsæg, & Colquhoun, 2014), this species demonstrates the highest mortality of all cleaner fish species tested in salmon aquaculture. The common reasons for high mortality (up to 48%) are mechanic damages and bacterial infections. Operating costs will therefore be associated with replacing the lost cleaner fish, treatments and changing production operations that cause damage in lumpfish.

Another problem is that the feeding activity of lumpfish varies among individuals. According to Imsland et al. (2014) more than 60% of the lumpfish used in the experiment were not feeding on lice. Indirect cost from the lost efficiency should be taken into account. In addition, according to current regulations producers are required to feed cleaner fish in the absence of its natural prey. As pointed out by Imsland et al. (2014) feeding lumpfish in cages is necessary even if sea lice are available, because variety in feeding will provide a better “appetite” for lice. The need for additional fish feed and feeding systems for cleaner fish also leads to increasing operating costs.



## **Large smolt**

Salmon juveniles are usually released to sea cages as soon as they have smoltified, weighting about 70-100 g (Asche & Bjørndal, 2011). Until 2012 the maximum individual weight of salmon juveniles to be released to sea water was limited to 250 g. A production method where larger and more robust smolts (postsmolts) are transferred to sea cages, was approved by Norwegian authorities in 2012. The changes in regulations allow the production of juveniles up to 1000 g in land-based or semi-closed systems under special permit (Akvakulturdriftsforskriften, 2008).

This production method has a number of advantages, including the prevention of sea lice spread. According to Nofima (n.d.), larger postsmolt have better survival and grow faster. Reducing the time at sea by 6-7 months optimises production by shortening the rotation period. As noted earlier, production volume is limited by MTB. By using larger smolt in combination with standard smolt producers achieve a production volume closer to MTB so that production capacity of the licence is fully utilised.

An abatement effect in terms of both salmon lice and fish escape is achieved by reducing the growing period in open cages. This was the argument used by the working group in the evaluation of applications for “green” licences (Furuset, 2014b). There are no estimations of how much the infestation pressure can be reduced, however. Since this method was considered effective by the expert group and the licences were given to applicants in Groups A and B, it can be assumed that in combination with other abatement methods, this will ensure sea lice level under 0.25 lice/fish. Without additional measures, the abatement effect will be lower.

The investment period for this method is equal to the production period at sea, which is 6-7 months shorter than usual or about 10 months. The production cost of 250 g smolt as estimated by SpareBank1 (Stephansen, 2015) is about 14 NOK per fish. The average market price of ordinary smolt (70-100g) in 2013 was 10 NOK with average production costs of 9.61 NOK per smolt (Directorate of Fisheries, 2014a). If the same profit margin is assumed for 250 g smolt, the price would reach 14.56 per smolt. The difference in prices equals 4.56 NOK and indicates investment cost per fish which means 912 000 NOK for 200 thousand salmon.

There is little information on how the shift to production with larger smolt might increase operating costs. The positive effect on costs due to better use of resources and lower production risks is significant and should be included in the model.

## Use of fish with enhanced resistance to lice

According to the Nofima report (Gjerde, 2013), it is possible to increase resistance to sea lice infection in salmon through selective breeding. The project results also show that selection for this character does not influence the performance of other genetic characters.

There is no particular gene that controls lice susceptibility. Gjerde (2013) concluded that there should be multiple genes, each partly contributing to the level of resistance. It was concluded that with selection targeting only enhanced lice resistance, it would improve by 24% with each generation, giving a cumulative effect of 75% over five generations. This means that the number of attached lice per fish (both males and females) will drop from 3 to 0.75 on average (Figure 15). However, in reality the process will take longer, since selection is made on a complex of characters. It is assumed for the cost assessment that used alone the method will not ensure 0.25 lice/fish; a value of 0.3 is used in the model.

As pointed out by Gjerde (2013) selective breeding on its own is not a solution to the salmon lice problem, but over time it might reduce the need for chemical delousing and thereby reduce the risk of resistance development in the parasite. On the other hand, the effect of breeding will improve with each generation, which is an advantage compared with other methods. Investments (mainly in R&D) are made by the producers of aquaculture genetic materials and will increase the price of eggs. For salmon producers no additional costs are required by this abatement method.

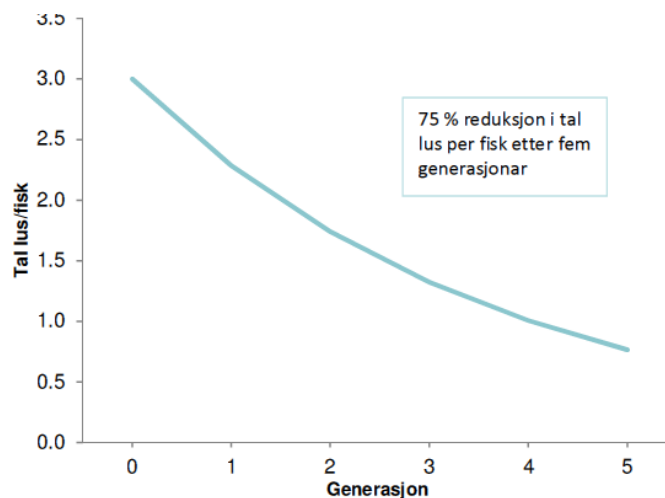


Figure 15. Expected development of salmon lice counts over five generations with selection only for resistance character. Source: Gjerde (2013).

Genetic material for salmon with enhanced lice resistance was put on the market in Norway last year by SalmoBreed AS. No price information has been available for this product or for lice-resistant smolt. For the assessment purposes, an increased average price of smolt of 10% is assumed, which gives 200 000 NOK investment per cage for one production cycle.

### **Mechanical delousing**

Mechanical delousing is used as an alternative to chemical treatment. The lice are mechanically removed from fish using sea water under pressure. Two producers offer their variants of mechanical delousing equipment in Norway today: Flatsetsund Engineering AS and SkaMik AS.

The Flatsetsund delousing complex was first tested in 2010. The results showed 57% to 68% removal of adult and pre-adult lice (A. Nilsen, Erikson, Aunsmo, Østvik, & Heuch, 2010). Since then the technology has been improved, achieving 95% removal of attached lice. Since the technology does not prevent infection after treatment, it should be used in combination with other measures to achieve a stable effect. Used alone, the abatement effect will be the same as with medical treatment. A value of 0.5 lice/fish is therefore used for the model.

The price of equipment is around 3 million NOK (G. B. Nilsen, 2011). The precise period of functioning for the technology is not known. For the assessment, a five year period of investment was used.

Mechanical delousing requires the use of boats, and the operation itself is labour intensive. Operating costs should therefore be calculated as cost of boat use and personnel working hours. SkaMik AS (Sekkenes, n.d.) calculated these costs for their technology as 0.05-0.1 NOK per kg treated fish depending on boat type. In addition, the equipment, which consists of pumping and energy units, pipes, lice collector etc., will need maintenance and repair.

Additional costs might be caused by damage and mortality of fish in the process and after the treatment. No stress-related changes were registered under tests of the technology and physical damage was minor (A. Nilsen et al., 2010), however, without properly adjustments of equipment fish can be seriously damaged.

## 5.2 Cost assessment results

### Model parameters

As seen from the description, there are both investment and operating costs for all abatement methods, except for improved genetic material and the use of large smolt, which have no influence on operating cost. Production loss should be taken into account for some of the technologies. Beneficial secondary effects might be significant and should also be quantified.

The investment period differs greatly among abatement technologies, and therefore, the choice of discount rate is important in order to provide an adequate comparison of costs. As noted earlier, the cost data for many technologies and methods is not available at the moment. A thorough micro-economic analysis incorporating biological and technical sub-models is needed to calculate the annual average costs of the methods with better precision. In the framework of this study the model is parameterized based on available data and following assumptions:

- Investment costs are calculated in NOK per 200 thousand fish (maximum number of fish in a cage) according to references provided above. Minimum cost values are used in the model.
- Standard production cycle in sea cages is 1.5 years.
- Values for abatement effect and technology lifetime are given according to the description of each technology.
- Discount rates of 4% and 6% are used.
- Since information on operating costs are not available (or its estimation is beyond the study scope), these costs are assumed to be proportional to investments. To define the effect of this parameter on the total annual cost, 10% and 20% from the investment cost is calculated.
- Where secondary costs occur, 5% of the investment cost is used for calculation.
- Where secondary benefits are achieved, they are calculated as 10% of the investment.
- Although these percentages are chosen arbitrarily for the model, they are believed to reflect what the real cost might be. The ratios between investment, operating cost and secondary effects chosen here serve the purpose of the model.
- Complex abatement methods, that were not covered in the study, such as closed and semi-closed production systems and off-shore farms, are modelled as one method with large investment (50 million NOK), a 20 years technology lifetime and abatement effect of 0 lice/fish. In reality the investments can be much higher. For example, as estimated by Marine Harvest, building a postsmolt production facility on land would cost 12-15 billion NOK

(Furuset, 2014e). Another example is a rejected by the expert group project of an off-shore salmon farm, that would require several hundred million NOK investment (Rønningen, 2014).

- The cost of traditional chemical treatment reported by Marine Harvest (P. M. Jensen, 2013) is included in the model. According to their estimations, the chemicals (Alphamax, Salmosan and Hydrogen peroxide) cost 1 million NOK per sea cage for one production period. This cost is treated as investment with production period 1.5 years. Abatement effect is assumed to be 0.5 lice/fish. Indirect costs are associated with lost growth due to treatment.
- For mechanical delousing and complex method the total costs were divided by 6 (average number of cages on one production site in Norway).

The data used for calculations is summarised in Table 5.

Table 5. Cost data of salmon lice abatement technologies and methods

| <b>Abatement method</b>                      | <b>Technology lifetime, years</b> | <b>Abatement effect, female lice/fish</b> | <b>Investment, NOK</b> | <b>Annual operating cost 10%, NOK</b> | <b>Other annual cost, NOK</b> | <b>Other benefits, NOK</b> |
|--|-----------------------------------|---|------------------------|---------------------------------------|-------------------------------|----------------------------|
| Lice shielding skirt                         | 3                                 | 0.1                                       | 213,000                | 21,300                                | 10,650                        | 0                          |
| Cleaner fish (farmed lumpsucker)             | 1.5                               | 0.1                                       | 300,000                | 30,000                                | 15,000                        | 0                          |
| Use of large smolt (250 g)                   | 1                                 | 0.25                                      | 912,000                | 0                                     | 0                             | 91,200                     |
| Use of fish with enhanced resistance to lice | 1.5                               | 0.3                                       | 200,000                | 0                                     | 0                             | 0                          |
| Mechanical delousing                         | 5                                 | 0.5                                       | 3,000,000              | 300,000                               | 150,000                       | 0                          |
| Complex method                               | 20                                | 0   | 50,000,000             | 5,000,000                             | 250,000                       | 500,000                    |
| Chemical treatment                           | 1.5                               | 0.5                                       | 1,000,000              | 0                                     | 50,000                        | 0                          |

## Results

Calculation results are shown in Table 6.

Table 6. Estimation of annual total cost of sea lice abatement technologies

| Abatement method                                | Annual total cost<br>(r=0,04;<br>10%) | Annual total cost<br>(r=0,04;<br>20%) | Change in annual<br>total cost, % | Annual total cost<br>(r=0,06;<br>10%) | Change in annual<br>total cost, % |
|---|---------------------------------------|---------------------------------------|-----------------------------------|---------------------------------------|-----------------------------------|
| Lice shielding skirt                            | 108,704                               | 130,004                               | 20                                | 111,635                               | 3                                 |
| Cleaner fish (farmed<br>lumpsucker)             | 255,033                               | 285,033                               | 12                                | 260,073                               | 2                                 |
| Use of large smolt (250 g)                      | 857,280                               | 857,280                               | 0                                 | 875,520                               | 2                                 |
| Use of fish with enhanced<br>resistance to lice | 140,022                               | 140,022                               | 0                                 | 143,382                               | 2                                 |
| Mechanical delousing                            | 187,314                               | 237,314                               | 27                                | 193,698                               | 3                                 |
| Complex method                                  | 1,779,848                             | 2,613,181                             | 47                                | 1,893,205                             | 6                                 |
| Chemical treatment                              | 750,109                               | 750,109                               | 0                                 | 766,909                               | 2                                 |

The cost difference between abatement methods is illustrated in Figure 16. As seen from the figure, new technologies are generally more effective and less costly than traditional bath treatment. However, 100% removal of sea lice would require much higher investment, and therefore, abatement costs are highest for “complex methods”. The use of larger smolt seems to have higher abatement costs in relation to other methods with the same abatement effect, despite the economic benefits of this method. This might be due to assumptions made in the model. More precise cost data at the firm level is required.

Figure 17 illustrates the results with higher operating costs. Increasing the contribution of this element did not have an influence on the pattern, but the total costs increased by 12-47%.

The change in results with increased discount rate is shown in Figure 18. The total cost was raised by 3-6%.

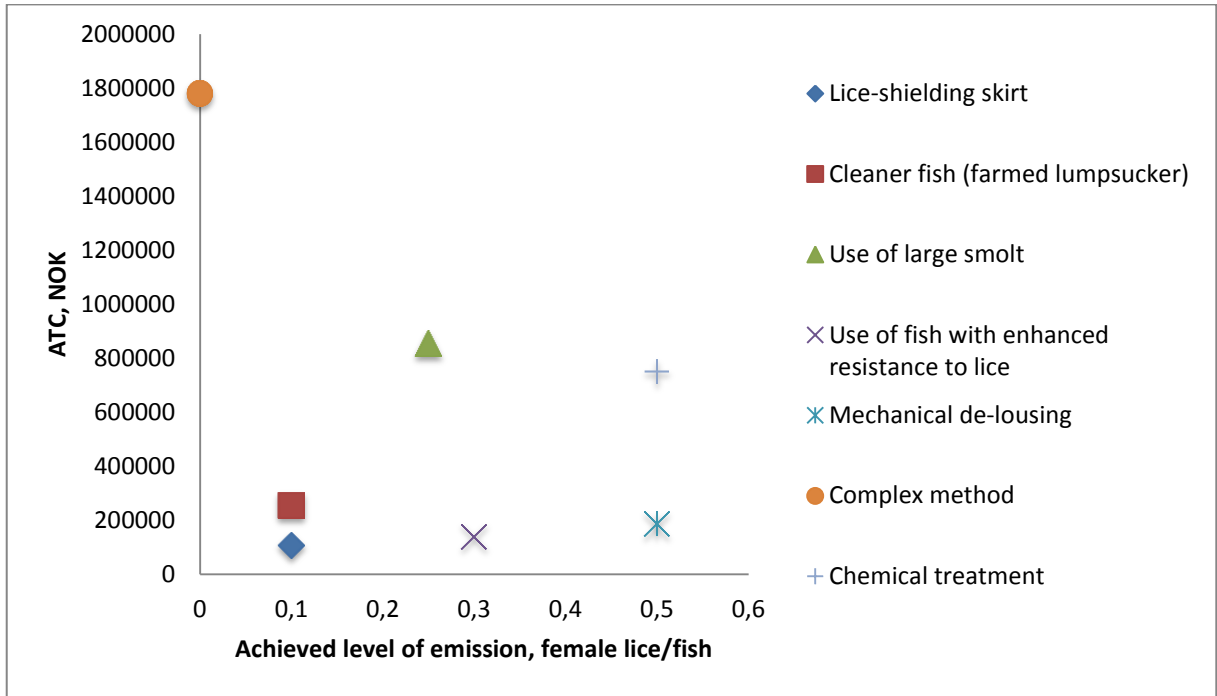


Figure 16. Average total cost of abatement with  $r = 4\%$ , operating cost = 10% of investment.

Even with such a schematic calculation, Figure 16 makes it clear that different sea lice abatement technologies are comparable in terms of cost. With more detailed data the annual total cost method is applicable for sea lice abatement, where different technologies have various characteristics and lifetimes. Such a model can be useful for the assessment of current policies and for the development of new pollution control instruments. The average costs calculated with the help of the equivalent annual cost method can be used for the purpose of abatement function construction. This represents the role of green licences in defining environmental controls in the industry. In the last chapter follows a summary and discussion of the findings in relation to the research problem.

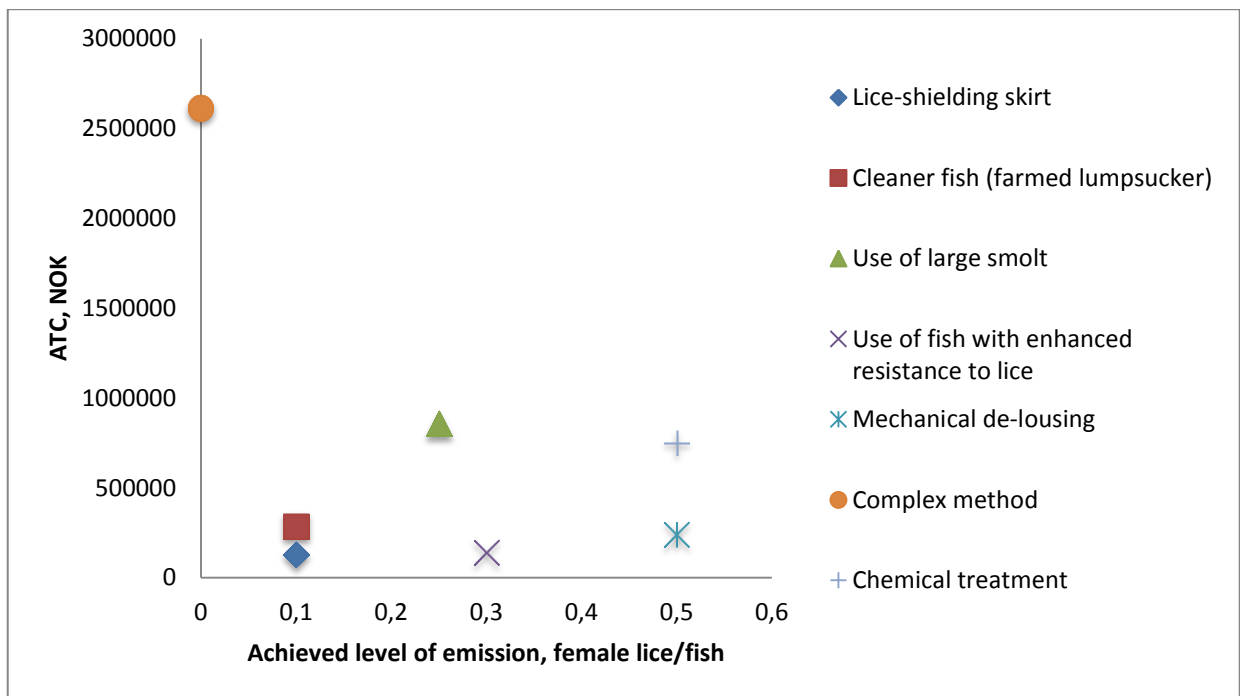


Figure 17. Average total cost of abatement with  $r = 4\%$ , operating cost = 20% of investment.

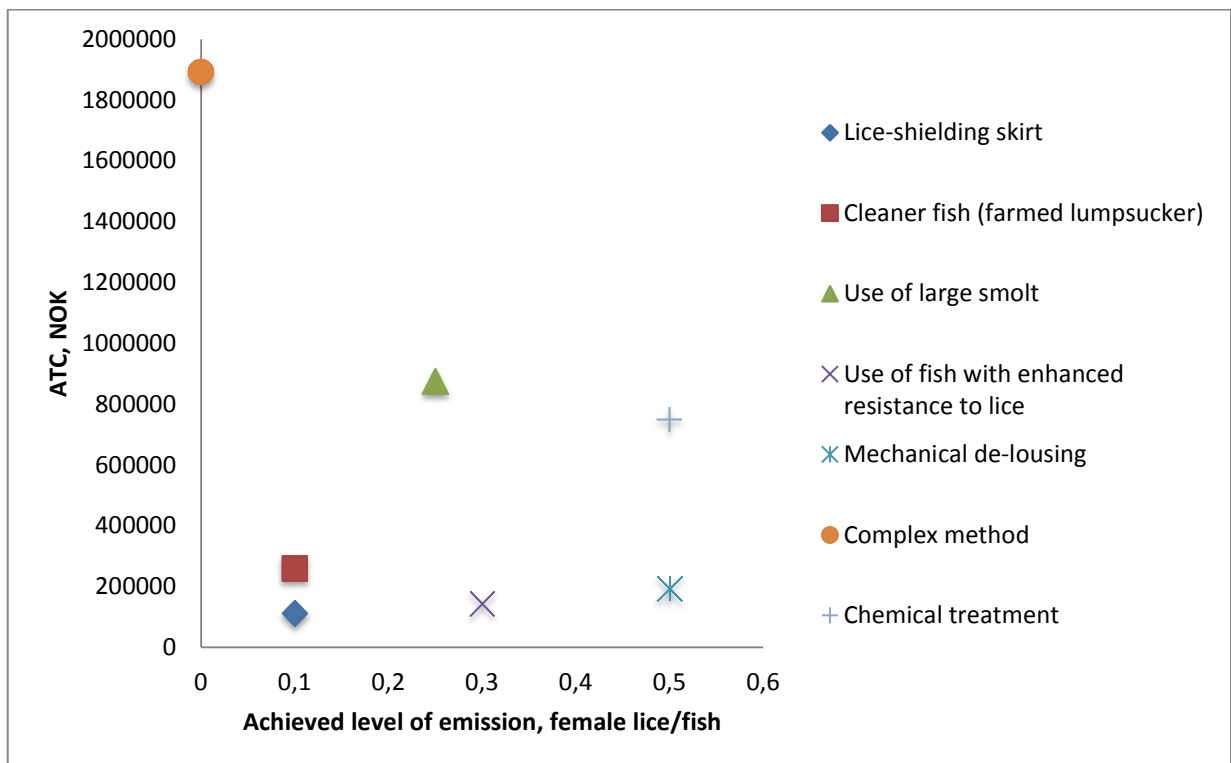


Figure 18. Average total cost of abatement with  $r = 6\%$ , operating cost = 10% of investment.



## Chapter 6: Discussion

As illustrated in Figure 16, abatement effect achieved with the help of new technologies is characterized by different costs at the farm level. It was expected that the higher abatement effect of a technology would require higher costs, however, the results of the assessment show that the same or even lower sea lice levels may be achieved at lower cost. For example, the use of cleaner fish gives the same result as the installation of a lice shielding skirt, but the latter is cheaper for the producer. The use of large smolt requires relatively high investments, and the abatement effect might be quite moderate.

It is important to note again that the assessment here is influenced by a number of limitations. The combinations of different abatement methods are not included and the data is lacking for many new technologies at the moment. Many producers use several techniques against sea lice. The most commonly proposed combination is the use of cleaner fish and a lice shielding skirt in addition to traditional chemical treatments. Therefore, it is likely that with more detailed data the costs of abatement strategies will be distributed in a different way. At the same time, there is little doubt about the fact that total avoidance of sea lice is the most costly solution. On the Figure 16 this is represented by a “complex method” with investment costs 50 million NOK. It was noted earlier that in reality the investments for building new production systems are even higher.

The method of equal annual cost has proved to be generally suitable for the assessment. However, the inconvenience is caused by the adjustment of production periods, which are not proportional to the periods of investment. Further development of the method is needed for more accurate results. This will require deeper insight in engineering and business economics and more detailed calculations of costs according to production process characteristics.

Despite the limitations, it is clear from the assessment that the choices of the technology will define the individual abatement cost functions from which the economy-wide function is aggregated. This is an important (but not the only one) contribution of the “green” licences experiment to the further development of the environmental controls in aquaculture. Introduction of the approved abatement methods has provided data for analysis of abatement costs, which is important for the design of environmental controls.

Knowing the abatement cost function contributes to the development of control instruments in two ways. First of all, together with the damage function it allows finding a socially optimal level of pollution. Today, this level is not defined for the sea lice pollution. As shown in Chapter 4, the limits are defined based on biological sustainability principle and they were changing quite often. It

is not clear to what extent the current limits of 0.5, 0.25 or 0.1 lice/fish ensure minimum harm for wild stocks, and which stocks are actually being protected. By introducing the thresholds of sea lice infestation pressure, the authorities were probably intended to protect both the industry and the environment, since the sea lice induce damage to production as well. Sea lice emissions are characterized by both “production-production” and “production – consumption” types of damage. Internal damage from lice originating from within farms is a major concern and makes the problem more complex. Existence of three different limits at the same time indicates the lack of clear goals and methodology in defining the target level of pollution.

If the sea lice infestation threshold were defined as a social optimum, the marginal damage function needs to be built. While internal damage is usually known, the environmental damage is difficult to quantify. There is no agreement about the extent to which sea lice originating from the farms affect the wild salmonids. Moreover, it seems to affect differently wild salmon and trout species. Pricing such damage is also a challenge. So far, the valuation studies were concentrated on the effects of sea lice on commercially exploited wild stocks. Other environmental services such as environmental regulation and culture-based services are not yet valued for the wild salmon.

A second application of abatement cost function in environmental controls design concerns introduction of market-based instruments. Knowing the location of the function the regulator can define the tax (subsidy) value per unit of emission. This can be done for any arbitrary level of pollution, which is relevant for the current situation with sea lice where the target level is defined on bases other than social optimum.

Whether the indirect instruments will be applied in the sector is difficult to say. So far the environmental policy in aquaculture is developing towards direct instruments. However, the “green” licences experiment has revealed a number of economic issues that will influence the next regulations, including the concerns on the effectiveness of command-and-control approach in the environmental regulations. The discussion around the “green” licences highlighted the lack of economic incentives for abatement when certain technologies are promoted under the regulations. A number of comments from the industry pointed out to the situation when a licence was granted to companies that experienced major problems with sea lice. At the same time, the farms where traditional methods worked well were not given priority. The choice of the most effective technologies by the expert group and the rejection of proposals were also questioned by the industry. Such reaction is expected when technological development is regulated by the state rather than the market.

This disadvantage of direct instruments caused proposals of another approach in the form of tradable MTB (Kråkås, 2015). This proposal shows that the industry is considering market-based instruments. If implemented, such measures could be the first attempt to establish indirect pollution controls in Norwegian aquaculture. If a permission for increasing MTB were granted in relation to abatement level, such system would be equal to a subsidy. An opposite measure, a tax per unit emission, is also a possibility, provided that a methodology is determined for defining the value of the tax/subsidy.

Another important issue highlighted by the regulations experience is the role of technologies and innovation in the environmental economics. As noted earlier, investment in the cleaner technologies is the only way to reduce emissions in a highly developed aquaculture industry where reduction of output is not an option. The application process for the “green” licences demonstrated a high variety of approaches to the technology choice. The differences in innovation capacity among producers were also illustrated, as some producers proposed their own technologies. The choice of abatement methods by a firm will depend on the regulations.

The conclusions made above should be seen in the framework of the limitations that are relevant for the method applied in the study. As all models in environmental economics, the theory of externalities and environmental control instruments are based on certain assumptions and do not take into account other factor that influence decision-making in the environmental policy. At the same time, political and social factors play an important role in regulation design. Practical issues in implementation of instruments, such as pollution tax, may result in prohibitive administrative costs, and therefore, other instruments should be chosen.

Time factor is also important to account for. A static model was used in the discussion on damages and benefits of pollution. However, since the abatement costs are mainly take the form of technological investment, the time factor becomes important for the analysis. This is demonstrated by figures in Table 6. The increase in costs with 6% discount rate compared to 4% was highest for the long-term investment projects.

The application of the externality theory to the problem of sea lice has also its limits. In Chapter 4 it was shown that sea lice have many of the attributes of chemical-based pollutants, and therefore the same concepts may be used for this problem as for other pollution problems. However, sea lice still differs from other pollutants due to its biologic nature. The main challenge of discussing the sea lice emissions is that populations of parasites develop according to ecological relationships, which makes them more unpredictable than the distribution and effects of chemical-based effluents.

There are epidemiological models for sea lice, but their application is influenced by a high grade of uncertainty.

The concept of externality then should be used with adaptations to a specific biological character of the sea lice pollution. This will require dealing with methodological issues, such as numerical expression of sea lice level. Today the number of lice of different development stages per unit biomass is used in research and in regulations. It is possible that another principle of defining the emissions would be required in order to calculate marginal damage and abatement cost functions and the target level of emission. Chemical-based pollutants for which the target levels are calculated are counted as the total amount of emissions in tonnes. Such measurements are easier to operate with. To provide a convenient measure for biological pollution such as sea lice, a biological modeling is needed. The new policy that included proposals on zoning principle is an attempt to find other measures of emission intensity. As mentioned earlier, it also takes non-uniformly mixed pollution nature of sea lice into account. Such measures might be based on the models of sea lice production similar to one proposed by Heuch and Mo (2001), where the total number of lice depends on the host biomass. With clear indicators of the total pollution and abatement related to costs, it will be possible to build an economy-wide marginal abatement cost function for the sea lice pollution.

The overall conclusion made from the study is that “green” licences regulations were an important step in improving knowledge about externalities problems in the aquaculture sector. Their role was particularly important in the analysis of the abatement costs, technological development issues and the design of effective environmental control instruments.

## References

- Aandhal, P. (2014). Scenarier i verdensmarkedet etter importstoppen i Russland [Video file]. Retrieved May 5, 2015, from [https://www.youtube.com/watch?v=V4nfva\\_WHiE&feature=youtu.be](https://www.youtube.com/watch?v=V4nfva_WHiE&feature=youtu.be)
- Akvakulturdriftsforskriften. (2008). *Forskrift om drift av akvakulturanlegg*. Retrieved May 5, 2015, from <https://lovdata.no/dokument/SF/forskrift/2008-06-17-822?q=akvakulturdrift>
- Aldrin, M., Storvik, B., Kristoffersen, A. B., & Jansen, P. A. (2013). Space-Time Modelling of the Spread of Salmon Lice between and within Norwegian Marine Salmon Farms. *PLoS ONE*, 8(5), e64039. doi: 10.1371/journal.pone.0064039
- Anon. (2012). *Lakselus og effekter på vill laksefisk – fra individuell respons til bestandseffekter*. Temarapport fra Vitenskapelig råd for lakseforvaltning nr. 3
- Aquaculture Act. (2005). *Act of 17 June 2005 no. 79 relating to aquaculture*. Retrieved May 5, 2015, from <http://www.fiskeridir.no/english/aquaculture/aquaculture-act>
- AquaGen. (n.d.). Øyerogn av atlantisk laks (*Salmo salar*). Retrieved May 5, 2015, from <http://aquagen.no/produkter/lakserogn/>
- Asche, F., & Bjørndal, T. (2011). *The economics of salmon aquaculture* (2 ed.). Pondicherry, India: SPI Publisher Services.
- Asche, F., Guttormsen, A. G., & Nielsen, R. (2013). Future challenges for the maturing Norwegian salmon aquaculture industry: An analysis of total factor productivity change from 1996 to 2008. *Aquaculture*, 396–399(0), 43-50. doi: <http://dx.doi.org/10.1016/j.aquaculture.2013.02.015>
- Asche, F., Roll, K. H., Sandvold, H. N., Sørvig, A., & Zhang, D. (2013). SALMON AQUACULTURE: LARGER COMPANIES AND INCREASED PRODUCTION. *Aquaculture Economics & Management*, 17(3), 322-339. doi: 10.1080/13657305.2013.812156
- Aspaker, E. (2014). *En forutsigbar og bærekraftig vekst i havbruksnæringen*. Paper presented at the Havbrukskonferansen, Oslo.
- Asplin, L., Johnsen, I. A., Sandvik, A. D., Albretsen, J., Sundfjord, V., Aure, J., & Boxaspen, K. K. (2014). Dispersion of salmon lice in the Hardangerfjord. *Marine Biology Research*, 10(3), 216-225. doi: 10.1080/17451000.2013.810755
- Beaumont, N. J., & Tinch, R. (2004). Abatement cost curves: a viable management tool for enabling the achievement of win-win waste reduction strategies? *Journal of Environmental Management*, 71(3), 207-215. doi: <http://dx.doi.org/10.1016/j.jenvman.2004.03.001>
- Bendiksen, E. Å., Johnsen, C. A., Olsen, H. J., & Jobling, M. (2011). Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture*, 314(1–4), 132-139. doi: <http://dx.doi.org/10.1016/j.aquaculture.2011.01.040>
- Berg, T. (2014). *Lakselus, fiskevelferd og bekjempelsesmetoder : en økonomisk betraktning rundt bruk av luseskjørt kontra tradisjonelle kjemiske metoder*. (Bachelor thesis), Universitetet i Nordland, Bodø.
- Bjørn, P. A., Finstad, B., & Kristoffersen, R. (2001). Salmon lice infection of wild sea trout and Arctic char in marine and freshwaters: the effects of salmon farms. *Aquaculture Research*, 32(12), 947-962. doi: 10.1046/j.1365-2109.2001.00627.x
- Boxaspen, K. (2006). A review of the biology and genetics of sea lice. *ICES Journal of Marine Science: Journal du Conseil*, 63(7), 1304-1316. doi: 10.1016/j.icesjms.2006.04.017
- Brooks, K. M. (2005). The Effects of Water Temperature, Salinity, and Currents on the Survival and Distribution of the Infective Copepodid Stage of Sea Lice (*Lepeophtheirus Salmonis*) Originating on Atlantic Salmon Farms in the Broughton Archipelago of British Columbia, Canada. *Reviews in Fisheries Science*, 13(3), 177-204. doi: 10.1080/10641260500207109
- Bye, T. (2014). Vannkraft og elektrisitetsøkonomi. In O. Flåten & A. Skonhøft (Eds.), *Naturressursenes økonomi*. Oslo: Gyldendal akademisk.
- Calanus AS. (2013). Luseskjørt. Fluidpermeabelt beskyttelsesnett mot påslag av lakselus og begroing av oppdrettsnøter. Virkemåte, testresultater og bruk.
- Cermaq. (2014). Laksens livssyklus - saltvann. Retrieved May 5, 2015, from <http://www.cermaq.com/wps/wcm/connect/cermaqno/home/fishfarming/Sea+water+production>
- Clement, A. (2014). *Chilean salmon situation*. Paper presented at the Havbrukskonferansen 2014, Oslo.

- Costello, M. J. (2006). Ecology of sea lice parasitic on farmed and wild fish. *Trends in Parasitology*, 22(10), 475-483. doi: <http://dx.doi.org/10.1016/j.pt.2006.08.006>
- Costello, M. J. (2009). The global economic cost of sea lice to the salmonid farming industry. *Journal of Fish Diseases*, 32(1), 115-118. doi: 10.1111/j.1365-2761.2008.01011.x
- Costelloe, M., Costelloe, J., O'Donohoe, G., Coghlan, N. J., Oonk, M., & Heijden, V. D. (1998). Planktonic Distribution of Sea Lice Larvae, *Lepeophtheirus Salmonis*, in Killary Harbour, West Coast of Ireland. *J. Mar. Biol. Ass.*, 78(3), 853-874. doi: 10.1017/S0025315400044830
- Deutsch, L., Gräslund, S., Folke, C., Troell, M., Huitric, M., Kautsky, N., & Lebel, L. (2007). Feeding aquaculture growth through globalization: Exploitation of marine ecosystems for fishmeal. *Global Environmental Change*, 17(2), 238-249. doi: <http://dx.doi.org/10.1016/j.gloenvcha.2006.08.004>
- Directorate of Fisheries. (2007). *Fiskeridirektoratets tiltaksplan mot rømt oppdrettsfisk. Visjon NULLFLUKT (2006-2007)*.
- Directorate of Fisheries. (2014a). Lønnsomhetsundersøkelse for matfiskproduksjon, laks og regnbueørret. Retrieved May 5, 2015, from <http://www.fiskeridir.no/statistikk/akvakultur/loennsomhet/matfiskproduksjon-laks-og-regnbueoerret>
- Directorate of Fisheries. (2014b). Oppdaterte rømmingstall. Retrieved May 5, 2015, from <http://www.fiskeridir.no/statistikk/akvakultur/oppdaterte-roemmingstall>
- Directorate of Fisheries. (n.d.). Fiskeridirektoratets statistikkbank. Retrieved May 5, 2015, from <http://www.fiskeridir.no/fiskeridirektoratets-statistikkbank>
- Economic Policy Department. (2014). *Veileder i samfunnsøkonomiske analyser*. Oslo: Fagbokforlaget.
- Elliott, M. (2003). Biological pollutants and biological pollution—an increasing cause for concern. *Marine Pollution Bulletin*, 46(3), 275-280. doi: 10.1016/S0025-326X(02)00423-X
- Eschenbach, T., & Smith, A. (1992). Sensitivity Analysis of EAC's Robustness. *A Journal Devoted to the Problems of Capital Investment*, 37(3), 263-276. doi: 10.1080/00137919208903073
- FAO. (2012). The state of world fisheries and aquaculture. Rome: FAO.
- FHF. (2014). Program rensefisk: Bruk av rognkjeks i merd. Retrieved May 5, 2015, from <http://www.fhf.no/prosjektdetaljer/?projectNumber=900979>
- Finstad, B., Bjørn, P. A., Todd, C. D., Whoriskey, F., Gargan, P. G., Forde, G., & Revie, C. W. (2010). The Effect of Sea Lice on Atlantic Salmon and other Salmonid Species *Atlantic Salmon Ecology* (pp. 253-276): Wiley-Blackwell.
- Fiske, P. (2013). Overvåking av rømt oppdrettslaks i elv om høsten 2010-2012. - Nina rapport 989.
- Flåten, O., & Skonhoft, A. (2014). *Naturressursenes økonomi*. Oslo: Gyldendal akademisk.
- Forskrift om lakselusbekjempelse. (2012). Forskrift om bekjempelse av lakselus i akvakulturanlegg. Retrieved May 5, 2015, from <https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140?q=Forskrift+om+lakselusbekjempelse>
- Forskrift om løyve til havbruk med matfisk. (2013). Forskrift om tildeling av løyve til havbruk med matfisk av laks, aure og regnbogeaure i sjøvatt i 2013. Retrieved May 5, 2015, from <https://lovdata.no/dokument/SF/forskrift/2013-06-24-754>
- Førsund, F. R., & Strøm, S. (2000). *Miljø-økonomi* (4. utg. ed.). Oslo: Gyldendal akademisk.
- Furuset, A. (2013). Panel rejects all appeals to Norway's "eco-friendly" salmon licenses. Retrieved from Intrafish website: <http://www.intrafish.com/news/article1382529.ece>
- Furuset, A. (2014a). Ikke flere skjønsmessige tildelinger. Retrieved from Intrafish website: <http://www.intrafish.no/norsk/nyheter/article1400846.ece>
- Furuset, A. (2014b). Kleiva vil bruke postsmolt og luseskjørt. Retrieved from Intrafish website: <http://www.intrafish.no/norsk/nyheter/article1389876.ece>
- Furuset, A. (2014c). Lakselus og pd-kostnader på 2-3 kr/kg. Retrieved from Intrafish website: <http://www.intrafish.no/norsk/nyheter/article1396133.ece>
- Furuset, A. (2014d). Norway's green licensing rounds: Who got in, who's out? Retrieved from Intrafish website: <http://www.intrafish.com/news/article1394574.ece>
- Furuset, A. (2014e). Vil ikke skje de nærmeste årene. Retrieved from Intrafish website: <http://www.intrafish.no/norsk/nyheter/article1399660.ece>
- Gjerde, B. (2013). Mot utval for auka motstandskraft mot lus hos laks. Report №16/2013: Nofima.

- Hamza, K., Rich, K., & Wheat, I. D. (2014). A SYSTEM DYNAMICS APPROACH TO SEA LICE CONTROL IN NORWAY. *Aquaculture Economics & Management*, 18(4), 344-368. doi: 10.1080/13657305.2014.959210
- Hanley, N., & Barbier, E. B. (2009). *Pricing nature : cost-benefit analysis and environmental policy*. Cheltenham: Edward Elgar.
- Helfand, G. E., Berck, P., & Maull, T. (2003). Chapter 6 - The Theory of Pollution Policy. In M. Karl-Göran & R. V. Jeffrey (Eds.), *Handbook of Environmental Economics* (Vol. Volume 1, pp. 249-303): Elsevier.
- Heuch, P., & Mo, T. (2001). A model of salmon louse production in Norway: effects of increasing salmon production and public management measures. *Diseases of Aquatic Organisms*, 45, 145-152. doi: 10.3354/dao045145
- Hevrøy, E. M., Boxaspen, K., Oppedal, F., Taranger, G. L., & Holm, J. C. (2003). The effect of artificial light treatment and depth on the infestation of the sea louse *Lepeophtheirus salmonis* on Atlantic salmon (*Salmo salar* L.) culture. *Aquaculture*, 220(1), 1-14. doi: 10.1016/S0044-8486(02)00189-8
- Horan, R. D., Perrings, C., Lupi, F., & Bulte, E. H. (2002). The Economics of Invasive Species Management: Biological Pollution Prevention Strategies under Ignorance: The Case of Invasive Species. *American Journal of Agricultural Economics*, 84(5), 1303-1310. doi: 10.1111/1467-8276.00394
- Hovland, E. (2014). Østenfor sol og vestenfor måne. Havbruksnæringen – et eventyr. In E. Hovland (Ed.), *Norges fiskeri- og kysthistorie: B. 5 : Over den leiken ville han rå norsk havbruksnærings historie* Bergen: Fagbokforlaget.
- IMR. (2014). Risikovurdering Norsk fiskeoppdrett 2013. Fisken og havet, særnummer 2–2014.
- Imslund, A. K., Reynolds, P., Eliassen, G., Hangstad, T. A., Foss, A., Vikingstad, E., & Elvegård, T. A. (2014). The use of lumpfish (*Cyclopterus lumpus* L.) to control sea lice (*Lepeophtheirus salmonis* Krøyer) infestations in intensively farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture*, 424–425(0), 18-23. doi: <http://dx.doi.org/10.1016/j.aquaculture.2013.12.033>
- Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2003). Chapter 11 - Technological change and the Environment. In M. Karl-Göran & R. V. Jeffrey (Eds.), *Handbook of Environmental Economics* (Vol. Volume 1, pp. 461-516): Elsevier.
- Jansen, P. A., Kristoffersen, A. B., Viljugrein, H., Jimenez, D., Aldrin, M., & Stien, A. (2012). Sea lice as a density-dependent constraint to salmonid farming. *279(1737)*, 2330-2338. doi: 10.1098/rspb.2012.0084
- Jensen, Ø., Dempster, T., Thorstad, E. B., Uglem, I., & Fredheim, A. (2010). Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. *Aquaculture Environment Interactions*, 1(1), 71-83. doi: 10.3354/aei00008
- Jensen, P. M. (2013). Lusebehandling koster flere kroner per kilo. Retrieved from Kyst.no website: [http://www.kyst.no/hovednyhet/?article\\_id=98252](http://www.kyst.no/hovednyhet/?article_id=98252)
- Johansen, R. (2013). Fiskehelse rapporten 2012. Oslo: Veterinærinstituttet.
- Kesicki, F., & Strachan, N. (2011). Marginal abatement cost (MAC) curves: confronting theory and practice. *Environmental Science & Policy*, 14(8), 1195-1204. doi: <http://dx.doi.org/10.1016/j.envsci.2011.08.004>
- Kolle, N. (2014). Gjennombruddet. In E. Hovland (Ed.), *Norges fiskeri- og kysthistorie: B. 5 : Over den leiken ville han rå. Norsk havbruksnærings historie*. Bergen: Fagbokforlaget.
- Kråkås, Ø. (2015). Høyringsuttale, havbruksmeldinga: Salmon Group.
- Kristoffersen, R. (2014). Fish parasites [PDF file]. Retrieved May 5, 2015, from [https://fronter.com/uit/links/files.phtml/1710667215\\$638644855\\$/Arkiv/FISH+HEALTH+\\_prcent\\_26+DISEASES/Bio2508\\_FishParasites\\_2014.pdf](https://fronter.com/uit/links/files.phtml/1710667215$638644855$/Arkiv/FISH+HEALTH+_prcent_26+DISEASES/Bio2508_FishParasites_2014.pdf)
- Krogstad, M., & Bugge, K. (2013). *Optimering og analyse av rotasjonsproblemet i oppdrettsbransjen. Effekten av en ny produksjonsregulering*. (Master thesis), Norges Handelshøgskole, Bergen. Retrieved from <http://brage.bibsys.no/xmlui/handle/11250/191722>
- Kvistad, A. (2014). Omfattende luseforskning – her er oversikten. Retrieved May 5, 2015, from <http://lusedata.no/fou/omfattende-luseforskning-her-er-oversikten/>
- Lakse- og innlandsfiskloven. (1992). *Lov om laksefisk og innlandsfisk*. Retrieved May 5, 2015, from <https://lovdata.no/dokument/NL/lov/1992-05-15-47?q=innlandsfiskloven>

- Lien, A. M., Stien, L. H., Grøntvedt, R., & Frank, K. (2015). Permanent skjørt for redusering av luspåslag på laks: SINTEF Fiskeri og havbruk AS.
- Liu, Y., Sumaila, U. R., & Volpe, J. P. (2011). Potential ecological and economic impacts of sea lice from farmed salmon on wild salmon fisheries. *Ecological Economics*, 70(10), 1746-1755. doi: 10.1016/j.ecolecon.2011.04.017
- Meeren, G. I. v. d. (2013). *Kasusstudie: Villaks og oppdrettslaks i et økosystemtjenesteperspektiv* (Vol. nr. 5/2013). Bergen: Havforskningsinstituttet.
- Ministry of Trade, Industry and Fisheries. (2013). *Verdens fremste sjømatnasjon*. (Meld. St. 22 (2012–2013)). Retrieved from <https://www.regjeringen.no/nb/dokumenter/meld-st-22-20122013/id718631/?docId=STM201220130022000DDDEPIS&ch=1&q=>.
- Ministry of Trade, Industry and Fisheries. (2014). *Høyring - forskrift om auke av maksimalt tillaten biomasse for løyve til akvakultur med laks, aure og regnbogaure*. Retrieved from <https://www.regjeringen.no/nb/dokumenter/Hoyring---forskrift-om-auke-av-maksimalt-tillaten-biomasse-for-loyve-til-akvakultur-med-laks-aure-og-regnbogaure-/id764283/>.
- Ministry of Trade, Industry and Fisheries. (2015). *Høringsnotat – melding til Stortinget om vekst i norsk lakse- og ørretoppdrett*. Retrieved from <https://www.regjeringen.no/nb/dokumenter/horing--melding-til-stortinget-om-vekst-i-norsk-lakse--og-orretoppdrett/id2076332/>.
- Ministry of Trade, Industry and Fisheries (2014). Nye tiltak mot lakselus [Press release]. Retrieved from <https://www.regjeringen.no/nb/aktuelt/Nye-tiltak-mot-lakselus/id2351302/>
- Møller, D., & Haaland, A. (2014). Pionertid ca. 1945-1973. In E. Hovland (Ed.), *Norges fiskeri- og kysthistorie: B. 5 : Over den leiken ville han rå norsk havbruksnærings historie* Bergen: Fagbokforlaget.
- Næs, M., Grøntvedt, R., Kristoffersen, A. B., & Johansen, B. (2014). Feltutprøving av planktonduk som skjerming rundt oppdrettsmerder for redusere påslag av lakselus (*Lepeophtheirus salmonis*). Faglig rapport 4. mars 2014.
- Naturmangfoldloven. (2009). *Lov om forvaltning av naturens mangfold*. Retrieved May 5, 2015, from <https://lovdata.no/dokument/NL/lov/2009-06-19-100?q=Naturmangfoldloven>
- Naylor, R., Hindar, K., Fleming, I. A., Goldberg, R., Williams, S., Volpe, J., . . . Mangel, M. (2005). Fugitive Salmon: Assessing the Risks of Escaped Fish from Net-Pen Aquaculture. *BioScience*, 55(5), 427-437. doi: 10.1641/0006-3568(2005)055[0427:FSATRO]2.0.CO;2
- NFSA. (2014a). Lakselusmiddelforbruket økte også i 2013. Retrieved May 5, 2015, from [http://www.mattilsynet.no/fisk\\_og\\_akvakultur/fiskehelse/lakselusmiddelforbruket\\_økte\\_ogsaa\\_i\\_2013.12980](http://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/lakselusmiddelforbruket_økte_ogsaa_i_2013.12980)
- NFSA. (2014b). Lakselusrapport: sommer og høst 2014: Norwegian Food Safety Authority.
- Nilsen, A., Erikson, U., Aunsmo, A., Østvik, A., & Heuch, P. A. (2010). Mekanisk fjerning av lakselus "FLS avlusersystem"- test av ejektorpumpe fra Flatsetsund Engineering AS *Veterinærinstituttets rapportserie. 11 – 2010*. Oslo: Veterinærinstituttet
- Nilsen, A., Viljugrein, H., Røsæg, M. V., & Colquhoun, D. (2014). Rensefiskhelse – kartlegging av dødelighet og dødelighetsårsaker *Veterinærinstituttets rapportserie · 12 – 2014*. Oslo: Veterinærinstituttet
- Nilsen, G. B. (2011). Gjennombrudd for "lusespyling". Retrieved from Intrafish website: <http://www.intrafish.no/norsk/nyheter/article1349375.ece>
- Nofima. (n.d.). Optimalisert postsmoltproduksjon (OPP). Retrieved May 5, 2015, from <http://nofima.no/prosjekt/optimalisert-postsmoltproduksjon-opp/>
- Nordbø, S. (2014). Rognkjeks tar lusa. *Namdalsavisa*. Retrieved from Namdalsavisa website: <http://www.namdalsavisa.no/Nyhet/article7178403.ece>
- NORM/NORM-VET. (2011). Usage of antimicrobial agents and occurrence of antimicrobial resistance in Norway. Tromsø / Oslo 2011. ISSN:1502-2307 (print) / 1890-9965 (electronic).
- Norwegian Environmental Agency. (2014a). Kobber og andre kjemikalier i fiskeoppdrett. Retrieved May 5, 2015, from <http://www.miljostatus.no/Tema/Hav-og-kyst/Fiskeoppdrett/Kobber-og-andre-kjemikalier-i-fiskeoppdrett/>



- Norwegian Environmental Agency. (2014b). Rekordhøyt forbruk av miljøskadelige lusemidler. Retrieved May 5, 2015, from <http://miljodirektoratet.no/no/Nyheter/Nyheter/2014/Mars-2014/Rekordhoyt-forbruk-av-miljoskadelige-lusemidler/>
- Norwegian Environmental Agency. (2014c). Tilførsler av næringsssalter fra fiskeoppdrett. Retrieved May 05, 2015, from <http://www.miljostatus.no/Tema/Hav-og-kyst/Fiskeoppdrett/Utslipp-av-naringsssalter/>
- Norwegian Institute of Public Health. (2013). Forbruk av legemidler i norsk fiskeoppdrett 2004 - 2013. Retrieved May 5, 2015, from <http://www.fhi.no/tema/legemidler/legemidler-i-fiskeoppdrett>
- Norwegian Seafood Council. (2014). Rekordhøy lakseeksport i 2014. Retrieved May 5, 2015, from <http://seafood.no/Nyheter-og-media/Nyhetsarkiv/Pressemeldinger/%E2%80%8BRekordh%C3%B8y-lakseeksport-i-2014>
- Norwegian Seafood Council. (n.d.). Presentation Norwegian Seafood Council. Retrieved May 5, 2015, from <http://seafood.no/Om-oss/Norges-sj%C3%B8matr%C3%A5d>
- NSL. (2014). Høyring-forskrift om auke av maksimalt tillaten biomasse for løyve til akvakultur med laks, aure og regnbogeaure.: Norske Sjømatbedrifters Landsforening.
- Olafsen, T., Winther, U., Olsen, Y., & Skjermo, J. (2012). Verdiskaping basert på produktive hav i 2050. Rapport fra en arbeidsgruppe oppnevnt av Det Kongelige Norske Videnskabers Selskab (DKNVS) og Norges Tekniske Vitenskapsakademi (NTVA).
- Olenin, S., Elliott, M., Bysveen, I., Culverhouse, P. F., Daunys, D., Dubelaar, G. B. J., . . . Vandekerkhove, J. (2011). Recommendations on methods for the detection and control of biological pollution in marine coastal waters. *Marine Pollution Bulletin*, 62(12), 2598-2604. doi: 10.1016/j.marpolbul.2011.08.011
- Perman, R., Ma, Y., Common, M., Maddison, D., & McGilvray, J. (2011). *Natural resource and environmental economics*. (4 ed.). Harlow: Pearson Education Limited.
- Porter, M. E. (1991). America's Green Strategy. *Scientific American*, 264(4).
- Rønningen, B. L. (2014). Salmar er klar til å ta kjempe-merdene til havs. *Hitra-Frøya*. Retrieved from Hitra-Froya website: <http://www.hitra-froya.no/havbruk/article9263215.ece>
- Ross, S. A., Westerfield, R. W., & Jordan, B. D. (2003). *Fundamentals of corporate finance* (6th ed. ed.). Boston, Mass: McGraw-Hill/Irwin.
- Sekkenes, H. (n.d.). Mekanisk avlusning SkaMik AS. Retrieved May 5, 2015, from <http://lusedata.no/fou/117-pa-mote-om-tiltak-mot-lus/>
- Shepherd, J., & Bachis, E. (2014). CHANGING SUPPLY AND DEMAND FOR FISH OIL. *Aquaculture Economics & Management*, 18(4), 395-416. doi: 10.1080/13657305.2014.959212
- SSB. (2014). Aquaculture, 2013, final figures. Retrieved May 5, 2015, from <http://www.ssb.no/en/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett/aar/2014-10-30>
- SSB. (2015). External trade in goods, December 2014, preliminary figures. Retrieved May 5, 2015, from <http://www.ssb.no/en/utenriksokonomi/statistikker/muh/maaned/2015-01-15?fane=tabell&sort=nummer&tabell=214686>
- Stephansen, E. (2015). *Store Penger i stor settefisk*. Paper presented at the TEKSET, Trondheim. <http://tekset.sircondesign.net/2015-2/>
- Stien, L. H., Nilsson, J., Hevroy, E. M., Oppedal, F., Kristiansen, T. S., Lien, A. M., & Folkedal, O. (2012). Skirt around a salmon sea cage to reduce infestation of salmon lice resulted in low oxygen levels.(Report). *Aquacultural Engineering*, 51, 21.
- Stormoen, M., Skjerve, E., & Aunsmo, A. (2013). Modelling s almon lice, *L epeophtheirus salmonis* , reproduction on farmed A tlantic salmon, S almo salar L. *Journal of Fish Diseases*, 36(1), 25-33. doi: 10.1111/j.1365-2761.2012.01415.x
- Strand, J. E. T. (2014). Smoltification [PDF document]. Retrieved May 5, 2015, from [https://fronter.com/uit/links/files.phtml/1710667215\\$145364612\\$/Arkiv/SALMONID+AQUACULTURE/3.+Smoltification+2014.pdf](https://fronter.com/uit/links/files.phtml/1710667215$145364612$/Arkiv/SALMONID+AQUACULTURE/3.+Smoltification+2014.pdf)
- Taranger, G. L., Karlsen, Ø., Bannister, R., Glover, K., Husa, V., Karlsbakk, E., . . . Svåsand, T. (2014). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science*. doi: 10.1093/icesjms/fsu132.
- Thorstad, E. B., Todd, C. D., Bjørn, P. A., Gargan, P. G., Vollset, K. W., Halttunen, E., . . . Finstad, B. (2014). Effects of salmon lice on sea trout – a literature review: Norwegian Institute for Nature Research.

Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O. T., Nilsen, F., . . . Jackson, D. (2013).  
Salmon lice – impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases*, 36(3),  
171-194. doi: 10.1111/jfd.12061