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Regulation of salmon aquaculture towards 2030: Incentives, economic performance and sustainability

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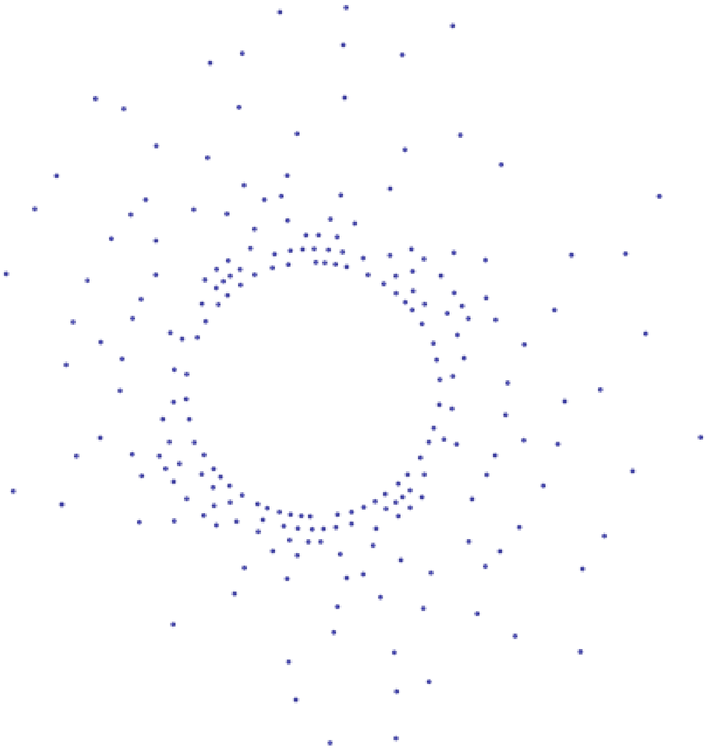

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Preface

This report is funded by the Norwegian Seafood Research Fund («Fiskeri- og havbruksnæringens forskningsfinansiering» - FHF), project «Havbruksforvaltning 2030», project no 901391.

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Abstract

This report discusses how the future regulation of salmon aquaculture can be designed to provide appropriate incentives for producers to innovate and operate such that the Norwegian society achieve sustainable and economic efficient outcomes. The report recognizes that salmon aquaculture production can lead to negative externalities to its marine environment in the form of emissions, parasites and diseases, and also to habitats in other parts of the world if feed resource use is not properly regulated and contributes to degradation of natural resources. However, for a given production quantity of farmed fish the level of negative externalities can be very different, depending on production technology and practices.

Furthermore, new knowledge and innovations has the potential to reduce the level of negative externalities per tonne of salmon produced. History has shown that the aquaculture industry through innovations have reduced environmental impacts and impacts of certain diseases significantly. The scope for further innovations that reduce environmental and biological impacts is probably huge. It is essential to provide the industry with appropriate incentives to invest in innovations and choose production practices that mitigate negative externalities. The design of the government's regulatory regime plays an essential role here.

In the future design of the regulatory regime it should be recognized that for each tonne of salmon biomass in the sea the emissions to the environment and external costs to society can vary significantly. Today, maximum allowable biomass (MAB or "MTB" in Norwegian) is a central quantitative regulation mechanism, both for companies, farm locations and larger production areas. In addition, the prevalence of sea lice at the farm site is measured and restricted. Through the traffic lice system government aims to regulate the impact of sea lice primarily originating from salmon aquaculture on wild stocks of salmon in thirteen production areas. Both sea lice performance at farm locations and estimated sea lice induced mortality in production areas is used to determine how much new maximum allowable biomass (MAB) will be offered to individual salmon firms for a predetermined price or through auctioning, and high estimated sea lice induced mortality can also lead to a reduction in a firm's MAB. Central questions are how the mechanisms for increase or reduction in production capacity should be in the future, which pricing mechanisms should be used for new production capacity, and if ocean based production technologies with very small or zero emissions (so-called closed or semi-closed technologies) should have different regulations than conventional inshore open cage technologies.

The government's rationale for restricting the allocation of new production capacity (e.g. MAB) can be (1) effects on market prices (and concern for ant-dumping measures), (2) effects on government revenue from auctioning of new capacity, (3) effects on the environmental sustainability and external costs. Concerning (1), it should be noted that

the Norwegian government does not aim to act as a regulator of world prices for salmon. Regarding (2), a narrow focus on government revenue from selling new production capacity fails to take into account the total economic effects of allocating new capacity in terms of value added, employment and tax revenue.

If government is primarily concerned with effects on environmental sustainability and external costs in allocation of new production capacity then central issues are emissions from different technological concepts and their productivity. The government should design regulations that maximize social welfare, taking into account differences in private and external costs between different technologies and provide incentives for companies to choose an appropriate mix of production technologies with respect to emission levels.

We present a bioeconomic model of salmon farming with farms using a common-pool resource, such as a fiord, and where there are negative externalities in the form of fish diseases and sea lice. The model has profit maximizing 'upstream' farm(s) and 'downstream' farm(s), where the upstream farms have negative external effects on the downstream farms, caused by hydrodynamic processes that carry diseases and sea lice from upstream to downstream farms. The model can be used to analyze different regulations with different levels of regional biomass etc. We show through the model how transition from individual profit maximization to joint profit maximization affects total profits and individual profits for downstream and upstream farms for four different sea lice restriction levels. We find that total profits increase in all cases, and also individual profit of the downstream farm increase. On the other hand, for the upstream farm profits are reduced, as it has higher disease and sea lice mitigation costs. In order to realize a higher joint profit, it is therefore necessary for the downstream farm to compensate the upstream farm so that its profits are not reduced. If voluntary collaboration does not lead to an equilibrium that maximizes welfare (here: profits) then government regulations which leads to optimal input choices and disease mitigation measures is an alternative. These regulations can include "emission quotas" for sea lice and disease pressure. It should be stressed, however, that appropriate regulations depend on quantitative empirical models of externalities and how mitigation measures influence them.

Econometric analysis of the relationship between production costs and maximum allowable biomass (MAB) shows that increasing MAB to allow production levels up to 30 to 40 thousand tonnes is associated with lower costs. In other words, there are increasing returns to scale up to these production levels. But according to the econometric results, economies of scale are exhausted beyond 40 thousand tonnes, implying that there are limited cost savings associated with increasing the size of the firm beyond that level of production.

We also tested the effect of sea lice prevalence at farms by estimating several econometric cost and profit function specifications. The results are mixed. Overall, an increase in sea lice prevalence is associated with an increase in production costs.

However, the effect is only statistically significant when full production costs is the dependent variable. For profits the effect of an increase in sea lice prevalence is significantly negative when we estimate a pooled model, i.e. lower sea lice prevalence is associated with higher profits, but not significantly different from zero when we include firm-specific effects in the profit function.

Looking towards 2030, current regulations may not satisfy the Norwegian parliament's expectations for growth in value creation, predictable and environmentally sustainable growth. There are several challenges with current regulations, both the design and the practice of these:

- The scientific knowledge base for the regulations is too weak in several areas. This applies, for example, to connections between aquaculture production, salmon lice populations and effects on stocks of wild salmonids.
- The requirements for documentation and the actual documentation of connections and status for influencing recipients are often too weak as a basis for decision-making for the administration.
- Public agencies are to varying degrees able to apply state-of-the-art research-based knowledge.
- There are different practices of regulations along the coast, partly based on different knowledge in different public agencies.
- The mechanisms for growth and reduction in production do not sufficiently reward companies that, through investments in innovations and better operations, reduce their impact on the environment.
- MAB is used as a regulatory mechanism to limit several types of impact simultaneously. For some types of impact, an indirect regulation such as MAB is imprecise and ineffective. If society, on the basis of a scientific knowledge base, finds that farm sites or larger sea areas are to be regulated in order to limit a type of impact, a more direct regulation of the impact can be more effective.
- The traffic light system has some generally valid premises in principle, but the practical implementation of the traffic light system may have significant weaknesses related to its knowledge base and design of mechanisms.

In sum, the current regulation should be further developed towards 2030 from restricting production to restricting environmental impacts, designing regulatory mechanisms that align aquaculture producer incentives with society’s sustainability concerns, and with stronger requirements for a documented knowledge base as made possible by new research results and digital innovations.

1. Introduction

The purpose of this report is to provide analysis and recommendations for future regulation of salmon aquaculture. A central rationale for public regulation of aquaculture production is market failure related to biological and environmental externalities to other economic agents and the aquatic ecosystem. By ‘market failure’ we mean that private markets are not able on their own to provide outcomes which are desirable from society’s point of view. Individual salmon firms do not sufficiently internalize in their economic decision making the effects their production activities have on other economic agents.

Aquaculture represents an opportunity for sustainable growth in food supply and incomes for many countries across the globe. Aquaculture sectors have environmental footprints, and thus require a balanced policy approach by governments. Global salmon aquaculture has experienced several periods of rapid growth, contributing to a growth in production from a few thousand metric tonnes in its infancy in 1980 to 3.2 million metric tonnes in 2018. Growth has been made possible by innovations, population growth and income growth. Process and product innovations have contributed to productivity growth and increasing global demand for salmon products among consumers.

Over the last decades, the salmon aquaculture sector has been subject to increased scrutiny due to biological and environmental problems related to fish diseases, effects on stocks of wild salmonid fish, and other emissions from farms. Salmon aquaculture has experienced business cycles reflected in fluctuations in production growth rates, prices and profits.

Salmon farming is basically a process of knowledge- and capital-intensive animal husbandry, with several biological risks at different stages of the production process. In Norway, the government’s aim is to increase the production significantly in a sustainable manner, and it has introduced several regulations aimed at facilitating sustainable growth.

Salmon aquaculture firms have been allocated coastal farm locations and license to produce through different mechanisms by government over time. Standard commercial salmon aquaculture licenses limit the biomass of live salmon in the sea and thus production at the farm, regional and national level. There are also other regulations and standards related to fish welfare, fish diseases, environmental emissions, effects on aquatic organisms and operational safety. This report will discuss a framework for future regulation of salmon aquaculture which can provide sustainable outcomes.

One can argue that further sustainable growth in Norwegian salmon production is possible the next decades with a properly designed policy regime that provides sufficient incentives to investments in research and innovation at different stages of the value chain. By ‘sustainable’ we mean, consistent with UN’s sustainable development goals, a growth that balances economic, social and environmental concerns of society. One aspect of the economic dimension is that capital and labor inputs are paid competitive wages relative to alternative employment in other sectors. Another aspect is that taxes and subsidies (e.g. R&D subsidies) are appropriately balanced with respect to government revenue needs, correction of market distortions and failures, and provide sufficient incentives for investments.

In this report we analyze some key features of salmon farming to shed light on implications for regulation. Section two presents important features of salmon aquaculture production processes, discuss government policy objectives and regulations, and discusses taxation issues. Section three provides an empirical analysis employing a panel data set on Norwegian salmon firms on patterns of productive and economic performance. Section four discusses future growth and some implications for taxation. Section five provides a summary and conclusions.

2. Considerations in salmon aquaculture regulation

This chapter discusses policy objectives and regulations for salmon aquaculture. It is recognized that the main market failure of aquaculture is biological and environmental externalities that provide costs to other salmon firms and society in general. Hence, much of the analysis will be centered around policies and regulations that allow salmon firms to achieve a high productivity and be internationally competitive, and at the same time limit the externalities to levels that are efficient or acceptable from society's perspective.

2.1. Government policy objectives and considerations

Aquaculture is a sector which represents both opportunities and challenges for society and government across countries. On the one hand, aquaculture can provide healthy nutrition, employment and income opportunities. On the other hand, as indicated above, it has biological and environmental externality risks which implies that it is a candidate for public regulation to mitigate market failures.

Both national policy objectives and multilateral agreements have implications for the regulation of aquaculture. Norway has together with other UN member countries adopted UN's 17 sustainable development goals, shown in Figure 2.1, which provides a general framework for assessing and balancing different economic, social and environmental sustainability considerations.[1] Due to its mix of challenges and opportunities aquaculture is a sector which is interesting to assess in terms of UN's 2030 agenda for sustainable development and UN's sustainable development goals.[2] UN's sustainable development goals cover a very broad set of challenges facing the globe, including poverty (goal 1), hunger (goal 2), decent work and economic growth (goal 8), responsible production and consumption (12), climate action (goal 13), life below water (goal 14) and life on land (goal 15).

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[1] See https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[2] See United Nations' website http://www.sustainabledevelopment.un.org. It states that the 17 Sustainable Development Goals (SDGs) '…*recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.*'

It should be stressed that “balancing” is a keyword here. It is a challenging task to translate UN’s sustainable development goals into specific policies and regulations for aquaculture. Policy makers must weigh economic, social and environmental considerations. The considerations may be very different across countries and species depending on e.g. economic stage of development, the nature of externalities for the aquaculture species, and the proximity to other user interests.

Figure 2.1. UN’s 17 sustainable development goals (Source: United Nations)[3]

Norway and other countries have through the so-called high-level panel "High-level panel for sustainable ocean economy" aimed at taking global leadership for sustainable use of the sea and highlight the importance the sea has for achieving the UN's sustainability goals.[4]

According to the high-level panel (Costello, C., L. Cao, S. Gelcich et al. 2019):[5]

- The sea can produce up to six times as much food as today in a sustainable way.
- Seafood production can grow sustainably with existing technology but be further increased with innovations.
- Proteins from marine aquaculture can be produced with lower climate emissions than proteins from animals on land.
- Proteins from marine aquaculture can be produced with a more efficient conversion of feed raw materials than proteins from animals on land.

The main Norwegian policy objectives for salmon aquaculture are expressed in the government’s white paper to the Norwegian parliament (Meld.St.16, 2014-15). It states the government should (p. 9-12):

- Develop an industrial policy which contributes to maximum economic value creation.
- Contribute to predictable and environmentally sustainable growth in aquaculture production of salmonids.
- Employ environmental sustainability as the most important factor in regulating further growth in salmon aquaculture.

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[3] See https://www.un.org/sustainabledevelopment/.

[4] See https://www.oceanpanel.org/about-the-panel.

[5] See https://www.oceanpanel.org/blue-papers/future-food-sea.

It has been stated in several documents (e.g. NTVA, 2012) and on many occasions by leading policy makers that Norway should aim to grow salmon aquaculture production from a current level of around 1.3 million tonnes to around five million tonnes in 2050 in a sustainable manner.

2.2. Salmon aquaculture production processes

Until now salmon have been farmed in open cages in seawater. The capital equipment of salmon farms includes cages, a floating barge for production surveillance room and feed storage, anchoring systems, and feeding systems. The production technology is highly automated through feeding systems and digital sensor technologies for monitoring the environment and live salmon. The role of the farm manager and labor is primarily monitoring of the farm, making feeding decisions, maintenance and assisting release and harvesting of live salmon in and out of the cages.

A typical salmon farm is of a scale that in production volume and sales revenue is many times larger than a typical agricultural livestock farm in most OECD countries. A farm may harvest in the range of 2000-6000 metric tonnes of salmon each year, and if the farm gate sales price is 40 NOK per kg this represents a sales value of 80-240 million NOK.[6] The most important inputs in terms of production cost shares are feed (typically 40-50%), salmon fingerlings, called smolts (9-11%), capital equipment depreciation (5-6%), and labor (7-8%).

The biological production process in salmon farming is basically one where salmon feed is converted to salmon biomass through growth. Farmed salmon are reared in open cages and rely on inflows of clean water with appropriate salinity, oxygen content and temperature. The flow of water also transports nutrients and faeces away from the cages, contributing to a healthy living environment for the salmon. Like other farm animals, salmon will not realize its potential in terms of feed digestion, growth and survival rates without an environment that provides sufficiently high levels of animal welfare.

Until recently salmon has been farmed in the coastal zone which is sheltered from the open ocean waves and winds. Through innovations which have led to more robust cages and other capital equipment salmon farms have gradually moved to farm sites more exposed to waves and winds, but also with greater water exchange and carrying capacity. The natural characteristics of water flows, sea temperatures and topographical conditions below the water surface influence the carrying capacity of a farm location, in terms of the

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[6] With an exchange rate of 10 NOK/EUR this is equivalent to a sales value of 8-24 million EUR.

total salmon biomass and production at the farms site, and the densities of salmon in the cages.

There are economies of scale in farm site production up to some levels related to capacity utilization of fixed inputs such as feed barges, cages and other capital equipment. Hence, a location with high bioproductivity and carrying capacity allowing for high salmon output and productivity levels can achieve lower unit production costs and higher profits. Potential farm sites along coastlines with appropriate conditions for salmon farming have different biophysical characteristics. If farm sites are sufficiently scarce and heterogeneous one can hypothesize that there are Ricardian or differential rents to be earned from the more productive locations.

Traditional Ricardian models of resource rent imply deterministic production processes, with no biological shocks which affect the absolute and relative productivity of different farm locations. However, this is not an appropriate representation of salmon aquaculture production processes. Like other live animals, salmon can be affected by diseases and parasites, such as sea lice. Biological and economic losses from diseases and parasites due to lower growth rates and higher mortality rates can be caused by production technology and practices, but also by the exposure of the location to external disease pressure from other farm sites and other human activities and natural conditions in the sea that entail disease risk. The history of salmon aquaculture has shown that there is a significant underlying biological risk caused by diseases and parasites. The magnitude of production risk has been estimated in several econometric studies (Tveteras, 1999; 2000; Kumbhakar and Tveteras, 2003), and compared with agriculture (Flaten, Lien and Tveteras, 2011).

Another source of externalities in salmon aquaculture is potential negative effects on wild stocks of salmonid fish through escape of farmed salmon, and sea lice from farmed salmon to wild salmonids. For owners of salmon fishing rights in rivers and recreational fishers this can lead to economic losses and reduced welfare. Organic emissions from salmon farms may also represent a negative externality to the marine environment if it is not sufficiently able to assimilate organic material and nutrients.

2.3. Theoretical framework for evaluation of regulation

Our theoretical basis for analysis of aquaculture regulation is primarily provided by microeconomic models of competitive markets and firms. It is fair to view the market for farmed salmon as a largely competitive market. Farmed salmon is a fairly homogeneous commodity traded in an international market with a large number of producers and buyers. However, the salmon market has several characteristics which deviate from the theoretical model of competitive markets. A long production cycle, biological production risk and imperfect information about several aspects of factors influencing demand and supply side are all departures from the benchmark competitive market model. Still, the competitive market model is a useful tool for analyzing the salmon market.

It can be argued that the main market failure in the salmon market is so-called *external effects* or *externalities* from salmon farms to other economic agents, in the form of e.g. diseases, sea lice, salmon escapees and organic emissions. Effects of production activities are external to a firm when they lead to reduced profits for other firms or reduced utility for individuals, and the firm itself do not internalize these negative effects in its own financial accounting and behavior. Diseases, sea lice and salmon escapees are far from pure externalities, because the firm which is the source of these will typically also have costs in terms of lost biomass and reduced profits. However, the costs of neighboring farms and wild salmon fishers are not necessarily taken into account unless there are regulatory mechanisms which facilitate that.

In a competitive market model the effects of externalities can be depicted as in figure 2.2. In this figure, the demand curve represents buyers' marginal willingness to pay for farmed salmon, and the supply curve represents the marginal cost of producing salmon. External costs lead to a discrepancy between private and social costs of production of farmed salmon represented by the difference between the green and blue supply curve. The supply curve before external costs only include the firms' private costs of production related to costs of inputs such as capital, labor and feed. For society, however, the costs to other economic agents caused by diseases, parasites etc., should also be included. When these external costs are included the equilibrium output, the production level where market surplus is maximized, is lower than if external costs were not present.

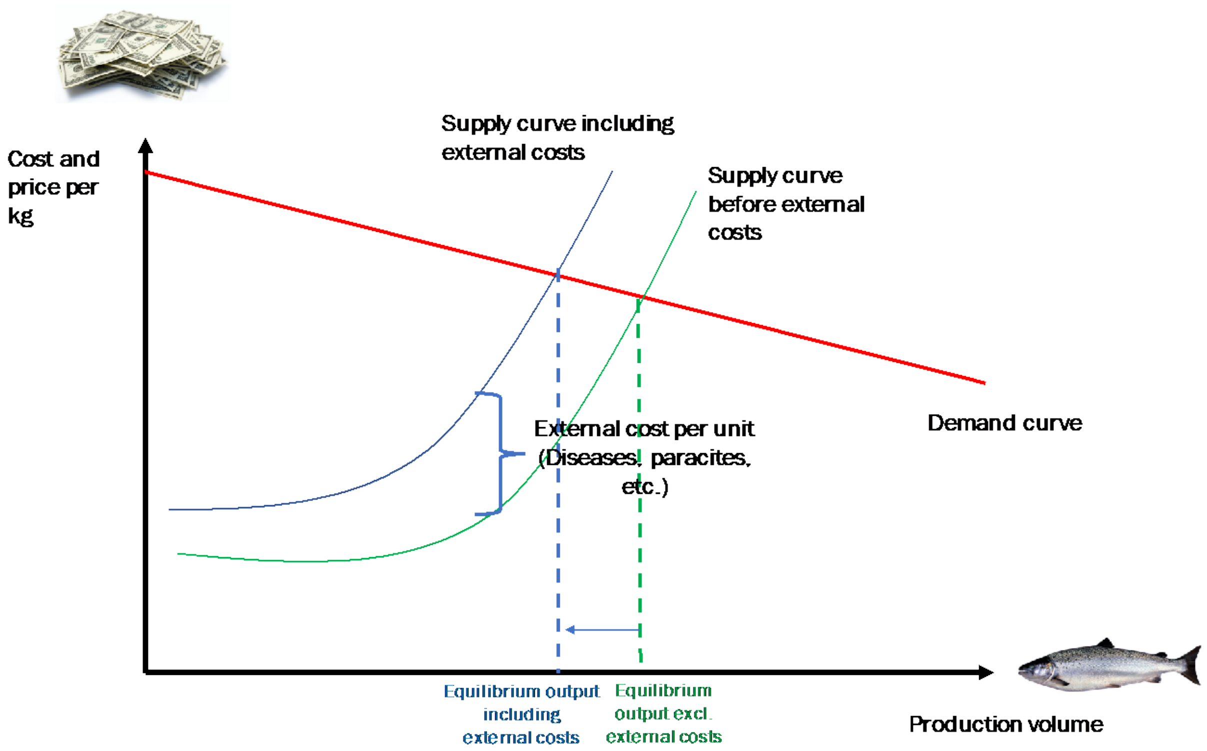

Figure 2.2. A salmon market with externalities

2.4. Externalities from aquaculture

The mechanisms of externalities in salmon aquaculture are richer than can be depicted in figure 2.3. The levels of external costs are related to technology, production practices and spatial factors. External effects caused by fish diseases, sea lice and escapees are related to hydrodynamic conditions in the region influencing the transport of infectious diseases and sea lice, the geographic configuration of farm sites in terms of proximity and location with respect sea currents, and technology and production practices at farm sites. It can be argued, given technology and production practices, that the risk of disease losses in a region increases with farms' geographic proximity, and total biomass of live salmon at farms in the region.

As illustrated in Figure 2.3 these are both externalities within aquaculture – between farms – and to other sectors – for example wild salmon stocks and fisheries and coastal fisheries. As mentioned earlier, they are not pure externalities in the sense that diseases, sea lice and escapees also have a negative productivity and profit impact on the emitting farm.

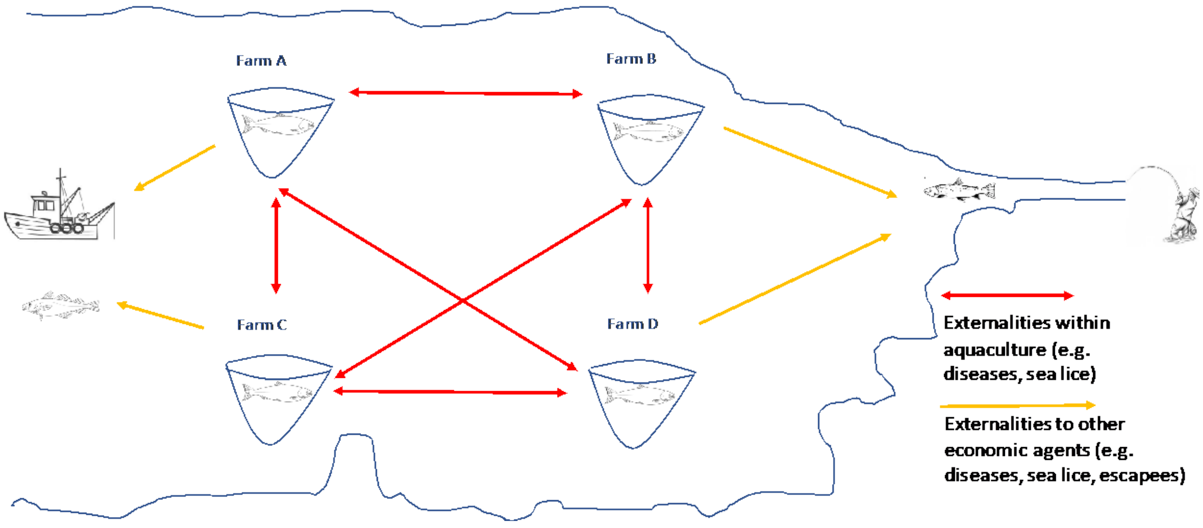

Figure 2.3. Salmon aquaculture and externalities (Fish diseases, sea lice, escapees)

Let us first analyze externalities within salmon aquaculture. Diseases and sea lice are sources of externalities from one farm to other farms. Diseases and sea lice will typically be transmitted from a farm to another through the ocean water. Sea lice is a parasite that feed on farmed and wild salmonid fish. Salmon, and particularly the small salmon smolt, can be negatively affected by sea lice in terms of health, growth and survival rate. The more salmon there is in a region the more potential hosts there are for diseases and sea lice. For sea lice, a higher farmed salmon population in a region mean that it is possible to sustain a higher population of sea lice, unless measures are taken that limit the ability of sea lice to use farmed salmon as hosts. One aspect of disease and sea lice externalities is that they may give rise to the relationships shown in figure 2.4. For a given technology and measures taken at salmon farms an increasing biomass of salmon, or maximum allowable biomass (MAB), is associated with increasing disease or sea lice pressure. This can lead to lower productivity in terms of production relative to the biomass of fish released into the cages or standing biomass in cages. In the next stage, this will typically also lead to higher production costs per kg of salmon.

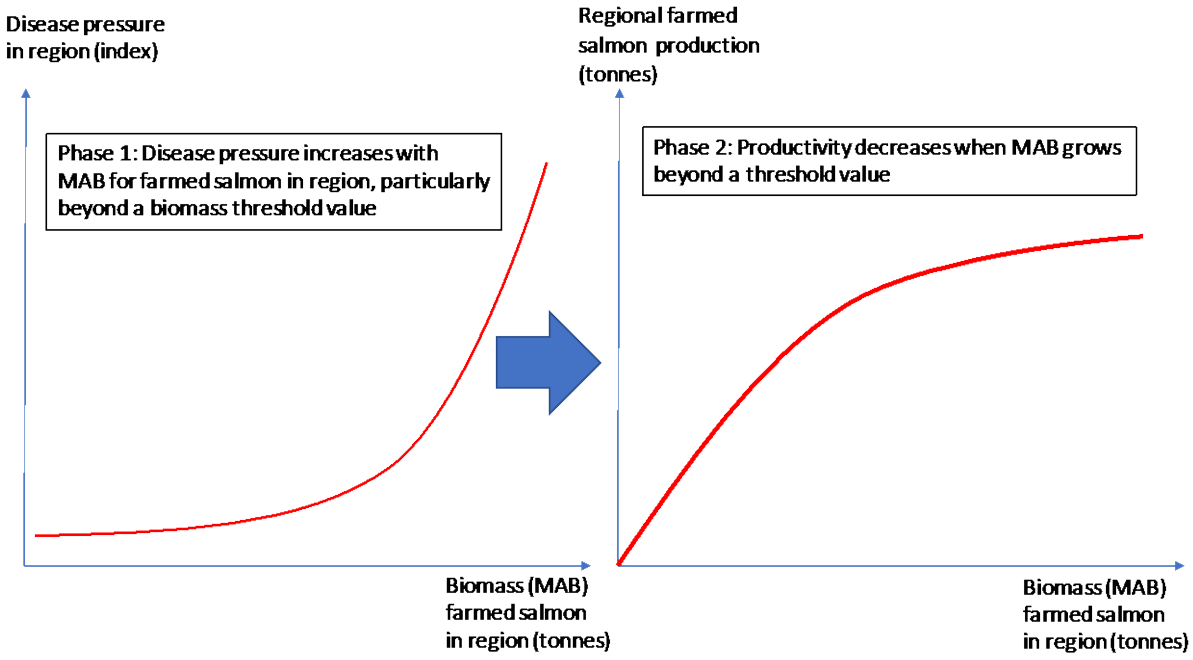

Figure 2.4. Possible relationships between allowable biomass (MAB), disease pressure and total production in a region

Sustainable growth of salmon aquaculture depends on innovations which can reduce disease and parasite pressure on both farmed and wild salmonids. An important role of policies and regulations is to stimulate investment in innovations and measures at farms aimed at this. Innovations and different measures at farms aimed at limiting the disease pressure and sea lice population may shift the curves in figure 2.4, leading to higher productivity. This is depicted in figure 2.5. In the left panel innovations lead to a reduction in the regional disease pressure for any given level of maximum allowable biomass. In the next stage, depicted in the right panel, this leads to higher productivity.

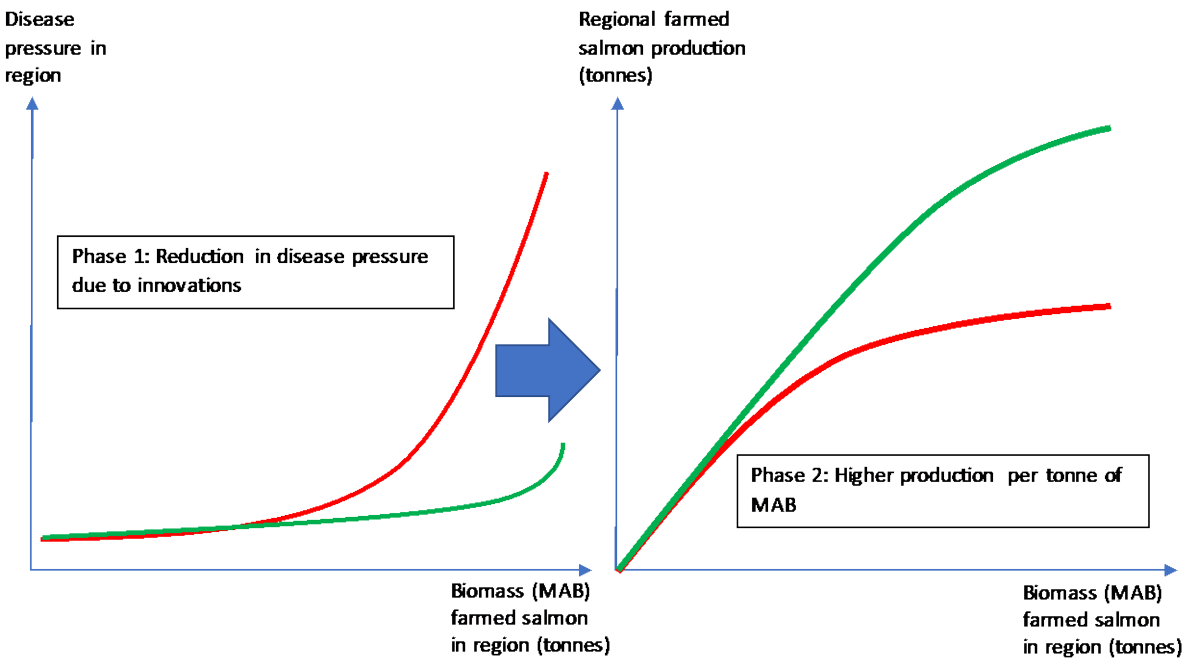

Figure 2.5. Reduction in disease pressure due to innovations, leading to higher productivity

It follows from the above that the potential productivity of an individual farm location is also influenced by its exposure to external disease and sea lice risks. From an economic point of view the productivity of a farm location can be characterized both by its expected (mean) level of primal and economic productivity, and by the riskiness of its biological and economic productivity (Tveterås, 1999;2000; Kumbhakar and Tveterås, 2003). We will see later that for individual firms there are large variations over time in biological productivity, production costs and profits.

A potential negative external effect from salmon aquaculture may be to stocks of wild salmonids, i.e. salmon and trout, and the value of recreational salmon fishing. As mentioned above farmed salmon may be hosts for sea lice. For a given technology and production practices it is reasonable to expect a positive relationship between the biomass of farmed salmon in a region and the sea lice population, as depicted in the left panel of figure 2.6. In the next stage sea lice may be transmitted to wild salmon. If there is a sufficiently high population of sea lice this may negatively affect the stock of wild salmonids, and even contribute to a stock which is lower than critical lower levels defined by society.

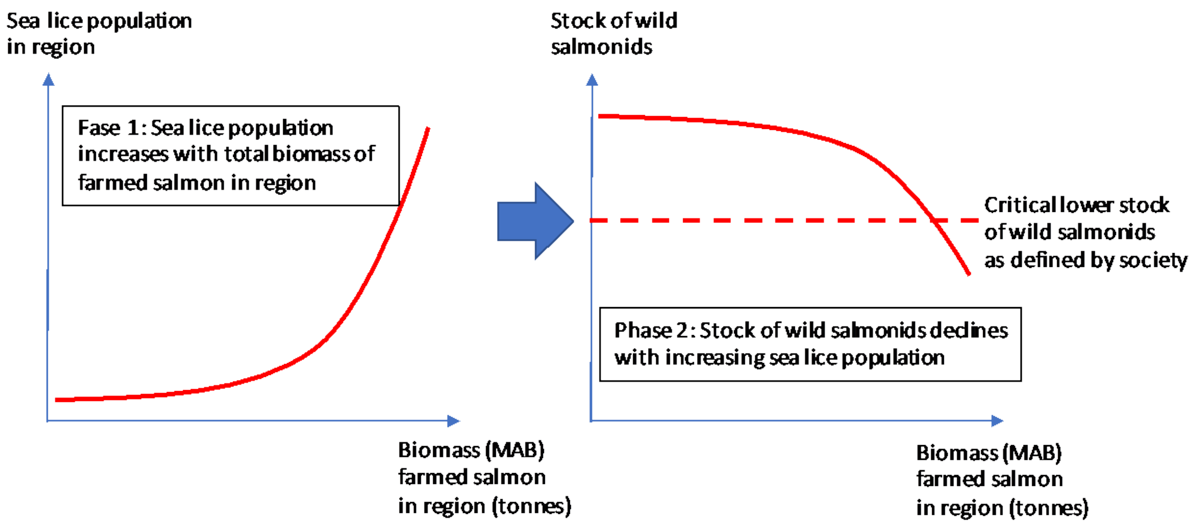

Figure 2.6. Possible relationships between maximum allowable biomass (MAB), sea lice population and stock of wild salmonids

Innovations that can contribute to reducing the regional sea lice population in salmon farms can allow for sustainable growth. The left panel of figure 2.7 depicts a reduction in the population of sea lice for a given level of farmed salmon biomass through innovations. In the next stage this leads to a lower pressure on the stocks of wild salmonids for any given level of farmed salmon biomass. Innovations thus allow for a higher maximum allowable biomass (MAB) of farmed salmon in the region.

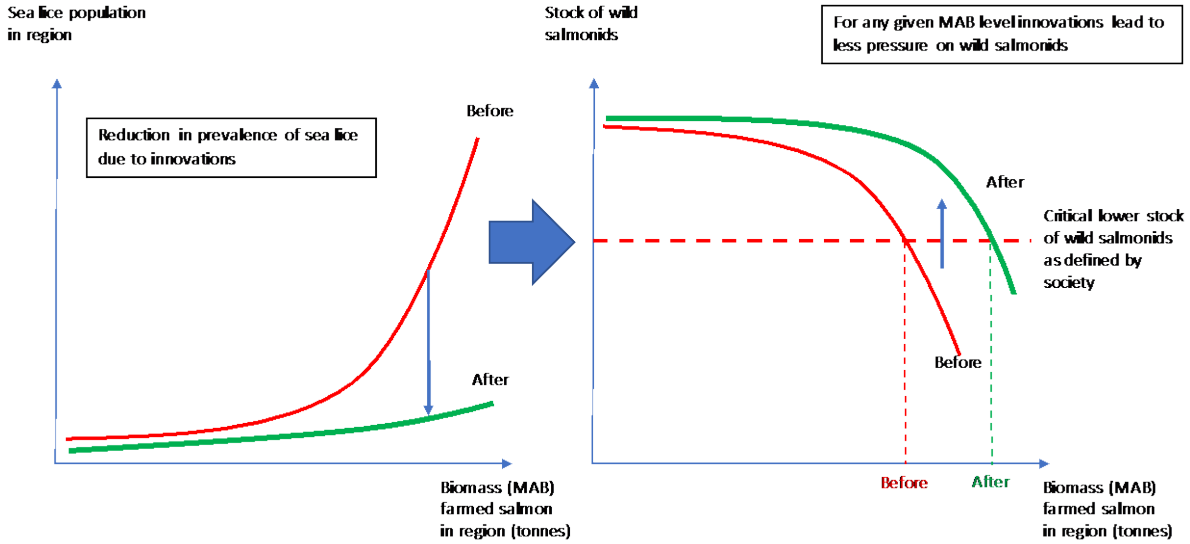

Figure 2.7. Reduction in sea lice population due to innovation and possible effects on stock of wild salmonids

Above we have argued that both externalities within salmon aquaculture and externalities to wild stocks of salmonid fish are related to the total biomass (or number of individuals) of farmed salmon in a region. For a given technology, external costs increase with the regional biomass of farmed salmon. Furthermore, at high regional biomass levels the external costs may increase more rapidly. We have also argued that innovations in salmon aquaculture may change the relationship between regional biomass of farmed salmon and external effects, leading to a lower external cost for a given regional biomass level. Government regulations can be employed to limit external costs to levels which are deemed acceptable by society. Furthermore, if it is a policy objective to increase salmon production in a sustainable manner, then regulations and other policy measures should also provide incentives for investments in innovations that reduce the external costs.

2.5. Maximizing social welfare with different salmon aquaculture production systems

A central question is how Norway can maximize welfare from salmon aquaculture? The concept of welfare includes the value creation and employment in the salmon aquaculture value chain itself, but also positive and negative economic effects on other firms and households in the society. In other words, salmon aquaculture firms should invest in a configuration of production technologies, geographic production locations and exploit economies of scale, such that society maximizes the total economic surplus when biological and environmental externalities are also included. This means that salmon firms should be subject to policies and regulations which lead them to internalize in their investment and production decisions biological and environmental external costs on other salmon aquaculture firms and society in general.

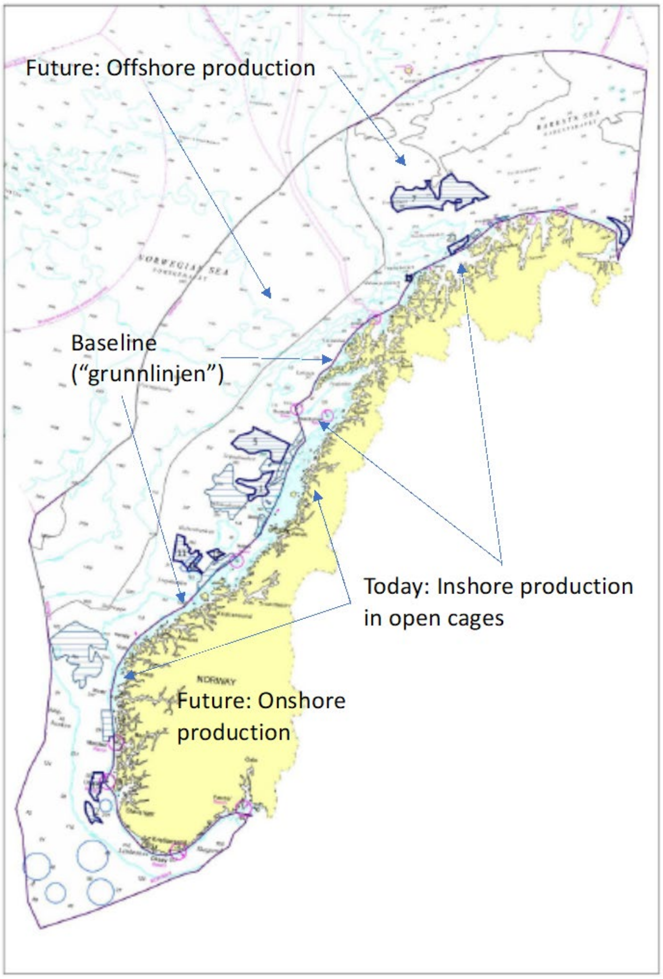

Figure 2.8. Production opportunities onshore, inshore and offshore with different production systems. (Map source: Directorate of Fisheries.)

Until recently the only mode of salmon grow-out production has been inshore farming in fiords and sheltered waters using open cages, well within the so-called baseline (“grunnlinje” in Norwegian). Figure 2.8 illustrates the production system alternatives for Norwegian aquaculture. Although the approximately thousand salmon farms in Norway use only a tiny fraction of the inshore sea area, it can be argued that due to biological and environmental externalities with much wider geographic effects farms actually occupy a significantly larger area inshore than what is only occupied by physical farm infrastructure. Still, salmon is using only a fraction of the Norwegian economic zone area that is available to aquaculture. The sea area inside the baseline is 89.091 km² while the total Norwegian economic zone area is roughly ten times larger, with an area of 878.575 km². The most distant areas of the Norwegian economic zone are currently not realistic to use for production due to logistic technology and cost challenges, but still there are vast offshore areas available to salmon aquaculture.

The dominant mode of production is still inshore farming using open cages based on small smolt from onshore farms. Through research and innovations, the salmon aquaculture industry now has an increasing range of production technologies available at different stages of maturity. These technologies differ with respect to several characteristics – productivity and production costs, location opportunities (onshore, inshore, offshore) and emissions (open, semi-closed or closed production technologies). The main challenge for salmon aquaculture is externalities from open cage farms inshore to other farms, other stakeholders and the environment. Today, however, there are several technological options in the form of different production systems to produce farmed salmon and mitigate emissions from open cage farms inshore:

(1) Produce salmon in open cage inshore farms with small smolt, i.e. the conventional production technology today.
(2) Reduce the production period in open cage farms inshore by increasing the production time onshore or inshore closed/semi-closed production of large smolt or post-smolt.
(3) Produce salmon in closed or semi-closed farms inshore.
(4) Produce salmon in offshore farms where distance from the inshore marine environment is sufficient to mitigate externalities.
(5) Produce salmon at land-based farms to harvest ready size, although this may probably be more competitive closer to final consumer markets.

These production systems have different internal costs and external costs. It is important to stress that within the production systems (1)-(5) there are several alternatives ways to influence both productivity and external costs through choices of production technologies and production activities. With low levels of biological and environmental external costs the more mature inshore open cage technology based on regular sized smolt is still the low-cost production system. However, with increasing external costs other production systems become more competitive.

Figure 2.9 depicts how alternative technologies can become competitive in the market. Let us assume that the supply curve (blue curve) of inshore open cage salmon aquaculture includes both internal and external marginal costs, implying that it includes external costs to other salmon firms and agents in society. Demand is initially low, leading to a market equilibrium where the conventional inshore open cage technology (blue curve) supplies all the salmon to the market, with production quantity Y_0 and market price P_0. As demand increases the conventional open cage technology experiences increasing marginal costs, also due to increasing biological and environmental externalities per unit. Hence, the supply curve - i.e. the industry marginal cost curve - becomes steeper as production increases. This creates an opening for alternative technologies, e.g. offshore and closed inshore and onshore production systems, to enter the market. These technologies start at higher marginal costs, but due to lower externalities than the conventional technology they become cost competitive as demand increases and allows for higher prices. In figure 2.9 the new demand curve leads to a new market equilibrium with the higher production quantity Y_1 and market price P_1 before new production technologies enter the market.

However, the high price makes it profitable for alternative technologies to enter the market. Let us assume that also for the alternative technologies both internal and external costs of production are included in the supply curve. The entry of alternative technologies shift the supply curve outward (green curve), and leads to a new market equilibrium with the higher production quantity Y_2 and market price P_2.

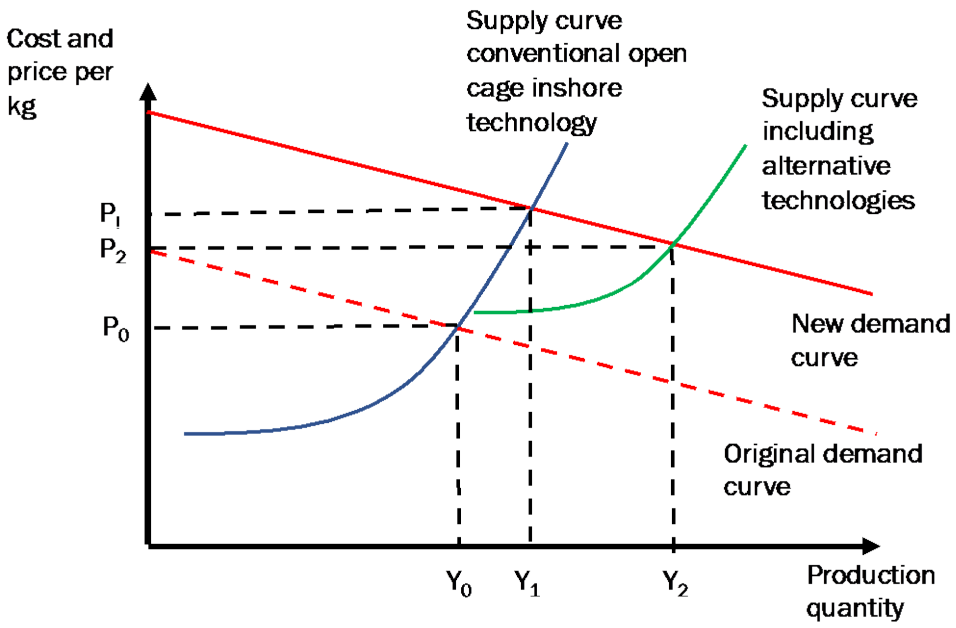

Figure 2.9. Demand and supply of farmed salmon with introduction of alternative technologies

As discussed earlier, salmon aquaculture is an industry with market failure in the form of externalities, which means that government must intervene. The market equilibrium in Figure 2.9 can only be socially efficient and emerge if external costs are internalized by producers for both the conventional and alternative technologies through appropriate government policies and regulations.

The challenge for government is to provide these policies and regulations that actually allow the socially efficient equilibrium to be achieved. This involves the following:

(a) Regulations must give firms license from society to make commercial investments in alternative technologies (1)-(5) and produce salmon based on firms' economic assessment of these alternatives. Currently, the licensing regime in Norway has not been developed to accommodate for all the alternative technologies in an efficient manner. Most notably, a license system for closed inshore aquaculture and offshore aquaculture need to be developed.

(b) Regulations should incentivize or require salmon aquaculture firms considering technologies (1)-(5) to internalize externalities to other salmon firms and society in general in their investment and production decisions.

(c) Regulations should allow firms to exploit economies of scale of these technologies, after taking into account internal and external economies and diseconomies of scale. This means that the scale economies should be exploited at the farm level and regional level. But it also implies that negative externalities should be incorporated in the scale decisions.
(d) Regulations should accommodate for further technological innovations in production systems (1)-(5). This means that regulations should allow for changes in productivity and externality performance, and provide appropriate incentives to innovations that increase productivity and reduce externalities.
(e) Finally, regulations need to account for government's incomplete knowledge about productivity, profitability and external costs of different technologies (1)-(5). This means that regulations should not be based on

Auctioning and trading of production licenses and emission rights are mechanisms that government can use when it has incomplete information about profitability, production costs and external costs.

2.6. Alternative regulatory measures for aquaculture

Several arguments for society to regulate production activities in aquaculture has been provided above. Market failure in terms of biological and environmental external effects provide a central rationale for regulation. However, it is of crucial importance that government aims to increase salmon aquaculture production in a sustainable manner from 1.3 million tonnes today to 5 million tonnes in 2050. The implications of growth ambitions for regulations are different than if salmon aquaculture was regarded as a mature sector that was not expected to increase production. High growth ambitions imply that it is necessary to reduce external effects and the environmental footprint per kilo salmon produced significantly. A significant reduction is only possible with innovations in key technology areas such as feed, feeding, animal health, and physical farm infrastructure. Consequently, policies and regulation must not only contribute to appropriate mitigation of external effects with the current technology but must also provide sufficient incentives for investments in technological innovation.

In principle, government has the following alternative policy measures and regulations at its disposition:

- Qualitative standards and requirements that influence firms' production activities – processes, routines and technologies. This includes veterinary requirements or standards in production and transportation of salmon, fallowing of sites, and technical standards for farm equipment (e.g. NYTEK regulation).

• Quotas which constrains total use of inputs in the production process, such as fish and feed. There are currently several restrictions on input use: (a) Maximum allowable biomass ("MTB" in Norwegian) of live fish at individual farm sites and company level. (b) Density constraint of 25 kg of live fish per cubic meter is also an input regulation. (c) Maximum 200,000 individual fish in a production unit (i.e. cage or pen). In earlier periods salmon aquaculture had restrictions on total cage volume and fish feed input.

• Quotas which constrain other biological populations or emissions from farms, such as organic emissions, emissions of sea lice. Currently, the population of sea lice is constrained through a restriction on the average number of adult female sea lice per salmon individual in a farm.

• Quotas which directly constrain production or harvest level of farm. So far, this type of constraint has not been introduced in salmon aquaculture.

• Monetary unit fees or taxes on production or harvest level. So far, such measures have not been introduced. A unit tax can reduce the output level and indirectly the level of emissions if these emissions are related to output level. However, unit taxes on output do not provide economic incentives to reduce the emission level per unit of output for the farmer.

• Monetary unit fees or taxes on emission levels, e.g. organic emissions and sea lice emissions. So far, such measures have not been introduced. Unit taxes on emissions provide economic incentives to reduce the emission level for the farmer. A challenge can be to measure the emissions and to set the tax at a level that provide the appropriate level of emissions.

• Fines or other types of sanctions on behavior or incidents that leads to serious negative external effects, e.g. fish escapees. The Norwegian aquaculture act stipulates such reactions.

• Regulation of geographic location of production or standing biomass of live fish. Geographic location of production and production levels is indirectly regulated both at the farm site level and regional level, through approved farm locations and production areas which have been designed along the Norwegian coast.

• Provide incentives to innovations which reduce external effects through public funding or mandated private funding of research & development (R&D). The rationale for a government intervention which influence the level of R&D investments is market failure which lead to insufficient private investments in R&D which would be profitable for the society. Such market failures are typically high economic risk of R&D and insufficient opportunities for investing firms to appropriate economic returns of own R&D investment. For example, the economic returns of many R&D investments by technology suppliers to salmon aquaculture are appropriated by their customers, the salmon farming companies through reduced production costs and higher profits.

- Require sharing of information on farm production and emissions, which can include production plans, monitoring of environmental parameters, reporting of unwanted emissions and other incidents with possible effects on the environment and other firms and stakeholders.

3. Regulation of production and externalities in Norway

In Norway, the current policy objective of the government and most of the political establishment is to allow ‘sustainable growth’ of salmon aquaculture. Until now farm sea lice concentrations and effects of sea lice on wild salmon stocks have become central sustainability measures (Meld.St.16, 2014-15). The sector is regulated using several instruments, which are described in this chapter.

Production growth in Norwegian salmon farming is based on estimated sea lice concentration at farms and the so-called traffic light system with its assessed impacts of sea lice on wild salmonid stocks. Government regulated increase or reduction of maximum allowable biomass (MAB) for companies and production areas are made on the basis of farm sea lice performance and estimated influence on stocks of wild salmon. Although other emission from salmon farms may have negative effects on the environment and other economic agents they have not been included as determinants of production growth. A primary objective of both (1) the sea lice regulation at the farm site level and (2) traffic light system (TLS) at the production area level related to sea lice is to limit the impact on wild stocks of salmonid fish. Another objective is to limit the impact within salmon farming, i.e. negative externalities between salmon farms leading to increased mortality and reduced production.

Government also regulates several other aspects of salmon production to safeguard animal welfare and limit escape of farmed salmon, disease outbreaks and various environmental effects to the aquatic environment and other stakeholders. The government’s means for maintaining animal welfare and limit externalities through the production process are mandated standards for production equipment and practices, fallowing periods for farm sites (i.e. no production) at regular intervals, mandated reporting of biological and environmental parameters to public agencies, and monitoring and inspections by public agencies.

3.1. Maximum allowable biomass (MAB) regulation

Since the salmon sector’s infancy in the 1980s the government has restricted the licenses to produce at farm sites and indirectly production volumes. First, salmon production was regulated through farm pen volume restrictions, then through farm feed quotas, and from 2004 through maximum allowable biomass.

The stock of live farmed salmon in the sea is restricted by government from the national level to the site level, as shown in Table 3.1. Individual firms need licenses for maximum allowable biomass (MAB, or in Norwegian "MTB- maksimal tillat biomasse"), which limits the maximum biomass of live salmon in the cages at any point in time during the year. Furthermore, firms need a location license to operate a farm at a particular coastal site, which is public property. The government also limit MAB for each licensed farm location, based on an assessment of the biological carrying capacity of the site. Each salmon firm can have several MAB licenses and licensed sites and can move their MAB around to their licenses sites. Most firms have several producing farm sites at any given time, and some large firms produce in several regions along the coast.

Table 3.1. Maximum allowable biomass (MAB, in Norwegian "MTB") regulation at different levels

Level	Comment
Firm	Each firm owns a number of MAB licenses with a specified MAB in tonnes, and with a specification of which farm sites and production areas MAB license can be used. The MAB licenses restrict the firm's total MAB volume.
Farm site	Total MAB volume in tonnes at farm site is restricted.
Production area	Since firms' MAB licenses is specified for production areas, the total MAB volume of a production area is also restricted.

In practice the government indirectly limit production at the national level through MAB, at the regional level through so-called production areas, and at the farm site level. This is indicated in Figure 3.1, which shows the ratio of production volume to MAB volume. The MAB regulation was introduced in 2004, replacing a previous indirect production volume regulation through feed quotas. Salmon farmers adapted to the MAB regulation during the first years after its introduction, and eventually reached an average production/MAB ratio of approximately 1.5-1.7. The variation we observe across firms in each year, as represented in Figure 3.1 by the standard deviation of production/MAB ratio, can be due to the intrinsic quality of firms' aquaculture locations, stochastic biological shocks related to e.g. diseases and sea lice, quality of management, and in particular the firms' ability to exploit the MAB capacity by having a sufficient number of MAB licenses and farm locations which it rotates production between.

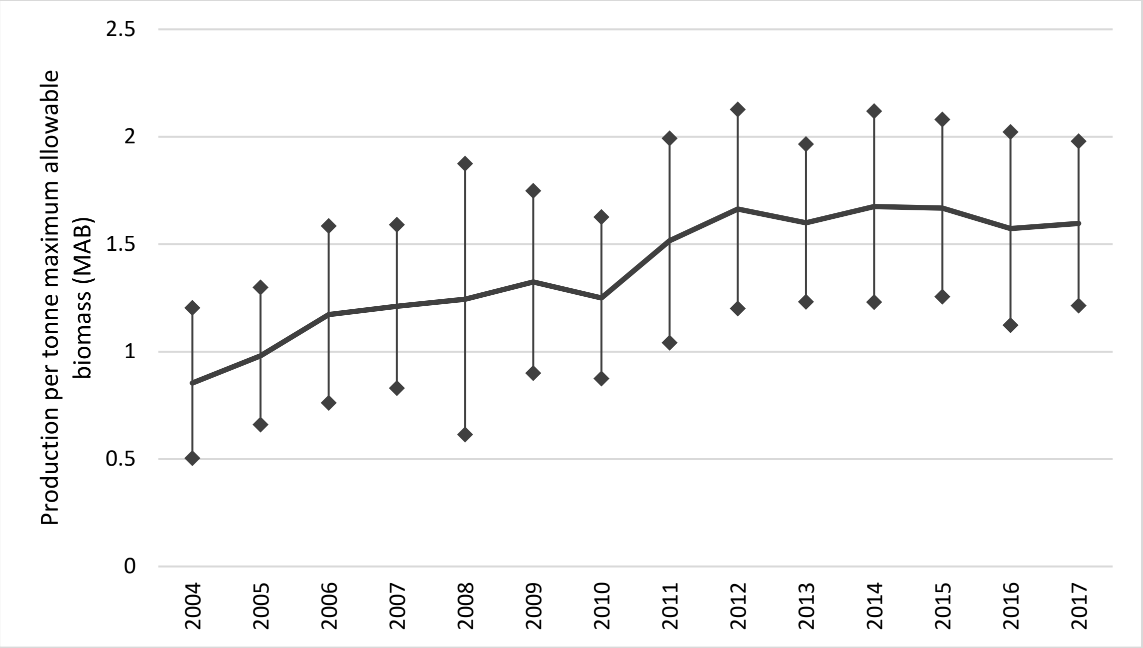

Figure 3.1. Average and st.deviation of salmon produced per tonne of maximum allowable biomass (MAB) of Norwegian salmon firms. The vertical lines represent +/- one st.dev.[7]

Until the beginning of the millennium new licenses were awarded with no fee or tax to the government. From 2002 this changed, as firms have generally paid a fee to the public for new MAB licenses, with some exceptions for ‘green’ licenses and ‘innovation’ licenses. The fee has in some periods been a fixed amount determined by government, but recently MAB has also been auctioned to the highest bidder. Revenue from the MAB fee is shared between municipalities, counties and central government according to a predefined formula. In principle, an auction of MAB should provide information about the economic rent in salmon farming as bids should be based on salmon firm’s estimates of discounted future cash flows. In the most recent auction in 2018 salmon firms paid an average of 195 KNOK per tonne of MAB, with bids ranging from 132 to 252 KNOK per tonne.

3.2. Sea lice regulation of individual farm sites

The sea lice regulation at farm sites aims to limit the number of sea lice per farmed salmon.[8] This legislation was announced in December 2012, and it came into effect January 1st 2013. It has been changed on several occasions. The limit is set at 0.2 adult sea lice per salmon during spring (weeks 16-21 for Vest-Agder to Nord-Trøndelag, weeks 21-

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[7] Data source: Norwegian Directorate of Fisheries.

[8] The regulation is in Norwegian entitled “Forskrift om bekjempelse av lakselus i akvakulturanlegg” (https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140).

26 Nordland-Finnmark). For the rest of year, the limit is 0.5 adult female sea lice per salmon.

Every week the number of female adult sea lice per salmon are counted at each producing farm site and reported to the government, as reported in the Barentswatch data base (https://www.barentswatch.no/fiskehelse/).

The incentive for the salmon farmer is to keep it down is related to the economic costs high sea lice concentrations have on the farm due to increased salmon mortality, reduced growth, and delousing costs. Violation of the sea lice limits can lead to a temporary reduction in the maximum allowable biomass (MAB) of the farm location (described later in a separate section). Furthermore, it influences the license to increase production in the future from the government. Farms with satisfactory sea lice counting can apply for increased MAB every second year when new MAB is awarded, as specified in §12 in the production area regulation and Chapter 3 in Capacity adjustment regulation (2020) (described in more detail later).

3.3. Production area - Traffic light system

The objective of the production area regulation – often called the traffic light system (TLS) - is to limit the impact of sea lice on stocks of wild salmonid fish (i.e. salmon and rainbow trout) in a larger area with many farms.[9] It came into effect in the beginning of 2017.

If the sea lice induced mortality rate for wild salmonids are assessed to be high then the consequence in principle, according to the TLS, should be that the total production of farmed salmon in that production area has to be reduced. The underlying rationale is that the prevalence of sea lice and their negative impact on wild salmonid stocks is related to the total stock (or production) of farmed salmon in the production area.

Table 3.2 shows the definitions in the traffic light system. If the sea lice induced mortality rate in a production area is estimated to be less than 10% then the environmental influence is regarded as “acceptable”, and the traffic light is green. Aquaculture companies in a green production area can receive an offer to increase their maximum allowable biomass (MAB) by 6%. If the sea lice induced mortality rate in a production area

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[9] The production area regulation is specified in the legislative document «Forskrift om produksjonsområder for akvakultur av matfisk i sjø av laks, ørret og regnbueørret (produksjonsområdeforskriften)» (https://lovdata.no/dokument/SF/forskrift/2017-01-16-61). The legislation came into effect 16. January 2017, and has been changed 7. July 2017, 20 July 2017, 20. Feb 2019, and 4. February 2020. Note that this legislation do not use the term “traffic light system” explicitly. The TLS term is used in different policy documents and research publications.

is estimated to be between 10% and 30% then the environmental influence is regarded as “moderate”, and the traffic light is yellow. Aquaculture companies in a yellow production area can receive an offer to increase their maximum allowable biomass (MAB) by 6%.

However, according to §12 in the legislation companies must also satisfy requirements on sea lice prevalence at their farm site, which we will describe later.

Table 3.2. Traffic light system for the 13 production areas

Traffic light	**Sea lice induced mortality rate for wild salmonids**	**Terminology used for sea lice induced influence on mortality rate / Environmental influence**	**Action on regional MAB***
Green	<10%	Low (“Lav” in Norwegian) / “Acceptable”	Offer to increase MAB by 6% (§11)**
Yellow	10-30%	“Moderate” (“Moderat” in Norwegian)	Keep MAB constant (§10)**
Red	>30%	High (“Høy” in Norwegian) or “Unacceptable”	Reduce MAB by a % determined by the Ministry in each round (§9)**

*MAB: Maximum Allowable Biomass. **Refers to the production area regulation, in Norwegian: «Forskrift om produksjonsområder for akvakultur av matfisk i sjø av laks, ørret og regnbueørret (produksjonsområdeforskriften)» (https://lovdata.no/dokument/SF/forskrift/2017-01-16-61).

The production areas and the traffic lights based on the assessment for 2019 is illustrated in the following map in Figure 3.2.[10]

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[10] The basis for the geographic division of production areas are found in https://imr.brage.unit.no/imr-xmlui/handle/11250/2374839?locale-attribute=no .

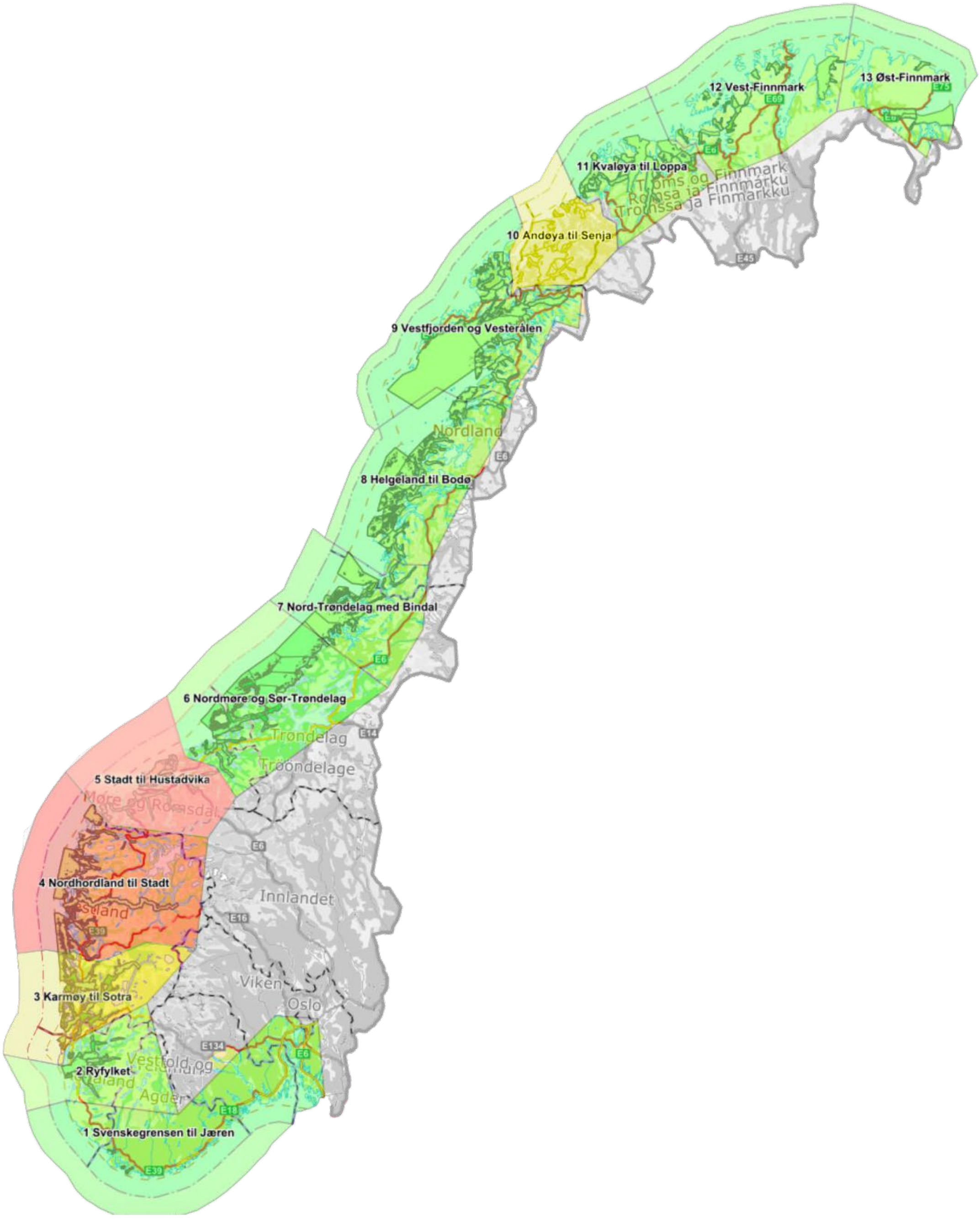

Figure 3.2. Assessment of the sea lice induced mortality rate for wild salmonids.[11]

The most recent advice to the government from the appointed steering group and expert group and was given in November 2019.[12] The expert group has for each year 2016-2019

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[11] Source: https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/rapporter/kart-til-pressemelding-fargelegging.pdf

[12] See government press release https://www.regjeringen.no/no/aktuelt/regjeringen-skrur-pa-trafikklyset-i-havbruksnaringen/id2688939/. The advice from the steering group is given in the document: https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/rapporter/rad-fra-styringsgruppen-til-nfd-2019.pdf. Analysis and advice from the expert group is given in:

provided an assessment of the sea lice induced mortality rate for wild salmonids to the government. These assessments are summarized in Table 3.3.

Table 3.3. Assessment of the sea lice induced mortality rate for wild salmonids by expert group*

Prod. Area	2016	2017	2018	2019
1	Low	Low	Low	Low
2	Moderate	Low	Moderate	Low
3	High	High	High	Moderate
4	Moderate	High	Moderate	High
5	Moderate	Moderate	Moderate	High
6	Moderate	Low	Low	Low
7	Moderate	Low	Moderate	Low
8	Low	Low	Low	Low
9	Low	Low	Low	Low
10	Low	Low	Low	Moderate
11	Low	Low	Low	Low
12	Low	Low	Low	Low
13	Low	Low	Low	Low

* Low (<10% sea lice induced mortality rate), Moderate (10-30% sea lice induced mortality rate), High (>30% sea lice induced mortality rate).
Source: “Vurdering av lakselusindusert villfiskdødelighet per produksjonsområde i 2019», p. 78 (https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/rapporter/ekspertgruppe-rapport_2019.pdf).

From the above table one can observe that the assessment has changed over time for several production areas. Already from 2016 at least one production area was assessed to have high sea lice induced influence (ie. >30%) on wild salmon mortality rate. However, before the last round in 2019 maximum allowable biomass has not been reduced in a production area as a consequence.

Up to seven different methodological approaches were used in each production area to assess the sea lice induced mortality rate. These methodological approaches have often

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https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/rapporter/ekspertgruppe-rapport_2019.pdf. In addition, there are several other documents that provide documentation.

not provided the same assessment for each production area,[13] and an overall assessment had to be based on an evaluation of the set of individual assessments by the expert group.

3.4. Change in maximum allowable biomass

The government's conditions for change in maximum allowable biomass based on sea lice performance are described in the production area (or "traffic light") regulation and in 2020 in the "Regulation on capacity adjustment of licenses for aquaculture grow-out farms for salmon and trout in 2020". [14]

It is a combination of production area performance and individual performance that determines the change in MAB. Farms in red production areas must reduce their MAB to 94% of original level, i.e. down 6% (Capacity adjustment regulation, 2020, Chapter 4). For farms in green production areas there is an offer to increase MAB by 1% (Capacity adjustment regulation, 2020, Chapter 1). The price for an additional metric tonne of MAB is set to 156,000 NOK.

The legislation also allows for an increase in individual firm maximum allowable biomass up to 6% regardless of the traffic light status of the production area (§12 in the production area regulation and Chapter 3 in Capacity adjustment regulation, 2020). In other words, even firms in production areas with red or yellow light can apply for an increase in biomass. The criteria for being allowed to increase MAB are one of the following:

(a) Having a production technology that does not release salmon lice larvae from cages into the surrounding ocean, and this has been documented by a qualified independent third party for the last production cycle and last 12 months.

(b) Firstly, having less than 0.1 adult female salmon lice per salmon with all lice counting (once a week) (MTIF, 2012) within the period 1st of April to the 30th of September. Alternatively, emissions of eggs and free-floating stages of salmon lice into the surrounding ocean from the farm, would have been equivalent to the corresponding number of fish with a lice level of 0.1 adult female lice on average per fish. Secondly,

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[13] See table 2, https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/rapporter/ekspertgruppe-rapport_2019.pdf, p. 30.

[14] See production area regulation (https://lovdata.no/dokument/SF/forskrift/2017-01-16-61) and "Regulation on capacity adjustment of licenses for aquaculture grow-out farms for salmon and trout in 2020" (In Norwegian: "Forskrift om kapasitetsjusteringer for tillatelser til akvakultur med matfisk i sjø av laks, ørret og regnbueørret i 2020") (https://www.regjeringen.no/contentassets/68986c2c2d6d4443b5a057718317a210/endelig-forskrift-om-kapasitetsjusteringer-2020.pdf).

salmon have not been treated with drugs against salmon lice more than once during the last production cycle.

Even if the farm exceeds the 0.1 lice level, there is still a possibility to increase production capacity. This can happen through two requirements. First, there cannot be more than 0.17 sexually mature female salmon lice in one counting within the period 1st of April to the 30th of September. Secondly, there cannot be observed a lice level higher than 0.1 more than three subsequent counting's in the period presented above.

3.5. Temporary reduction in MAB due to violation of sea lice limits

Farm sites which have violated the sea lice limit more than 10 weeks during the last six months of the last production cycle may have their MAB reduced at that farm site.[15] The legal basis for this is the farm sea lice regulation - "Forskrift om bekjempelse av lakselus i Akvakulturanlegg" - §5 and $8.[16] The MAB reduction can be significant – typically 50% to 100% reduction in farm site MAB - and is up to the discretion of the Norwegian Food Safety Authority ("Mattilsynet"). The time period of the MAB reduction can be around two years, and apply to the entire duration of the next production cycle.[17]

It should be noted that it is not the salmon company's MAB itself that is temporary reduced, just MAB at a particular farm site. Hence, if the salmon firm has one or more other sites with vacant MAB capacity it can transfer production to other sites. Consequently, the reduction will have a greater economic effect for small firms with only one or two farms sites.[18]

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[15] Example of press release by the Norwegian Food Safety Authority ("Mattilsynet") about temporary reduction in MAB: https://www.intrafish.no/pressemeldinger/mattilsynet-har-gitt-to-oppdrettsanlegg-varsel-om-mellombels-redusert-produksjon/2-1-787820.

[16] See Forskrift om bekjempelse av lakselus i Akvakulturanlegg" (https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140).

[17] For furter details see: https://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/fiske_og_skjellsykdommer/lakselus/kriteriene_for_redusert_produksjon_ved_langvarige_lakselusproblemer.23109 and https://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/fiske_og_skjellsykdommer/lakselus/retningslinje_midlertidig_reduksjon_av_produksjon_paa_grunn_av_vesentlige_overskridelser_av_lusegrensen.23019/binary/Retningslinje%20Midlertidig%20reduksjon%20av%20produksjon%20på%20grunn%20av%20vesentlige%20overskridelser%20av%20lusegrensen.

[18] A list of farms sites with temporary reduction in MAB due to sea lice limit violation is found at: https://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/fiske_og_skjellsykdommer/lakselus/oversikt_over_lokaliteter_som_har_faatt_varsel_eller_vedtak_om_redusert_produksjon_pga_lakselusproblemer.18040.

3.6. Economic effects of sea lice regulation and traffic light system

The traffic light system (TLS) and the sea lice restriction on individual farm sites can in principle have both negative and positive effects on productivity and profitability of salmon aquaculture. If these regulations incentivize firms to increase their efforts at reducing sea lice prevalence at farms, then one should expect more efforts aimed at sea lice mitigation measures.

Figure 3.3 plots the average weekly levels of sea lice at salmon farms for the period 2012-2020. The vertical line indicates the implementation of TLS in the first week of 2017. The prevalence of sea lice has exhibited a declining trend after 2012, when the sea lice regulation at farms was introduced. The reduction continued after the introduction of TLS in 2017 but has increased somewhat recently. The variation in sea lice prevalence over the year has also declined substantially after 2012 and also after the introduction of TLS.

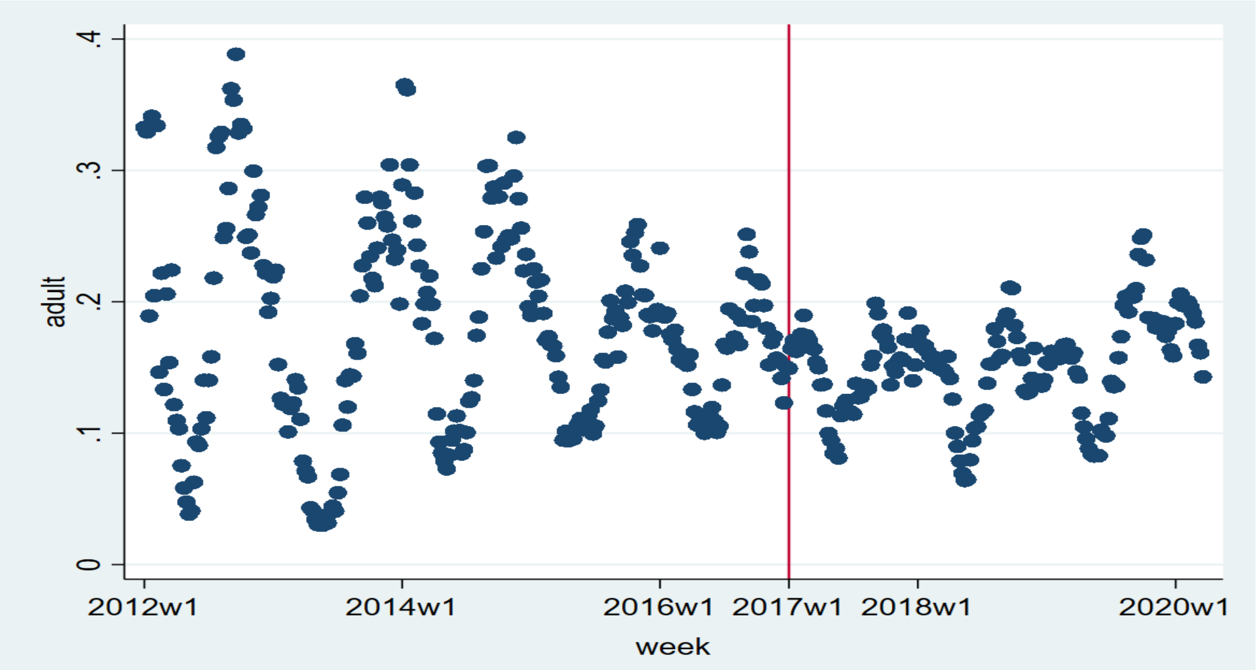

Figure 3.3. Lice prevalence (average number of adult female sea lice per salmon) among Norwegian salmon farms from 2012 to 2020 (Source: Barentswatch and Abate et al, 2020)

Figure 3.4 shows the percent share of farms with sea lice levels above limits set by the government. We see a decline in the share of farm sites that violate government sea lice regulation from 2012. Behind this decline is increasing resource use on preventive measures and treatments among salmon firms aimed at lower sea lice concentrations at their farms. After the TLS was introduced in the beginning of 2017 the share of farms that violated the limit declined further, but the increased again in 2019.

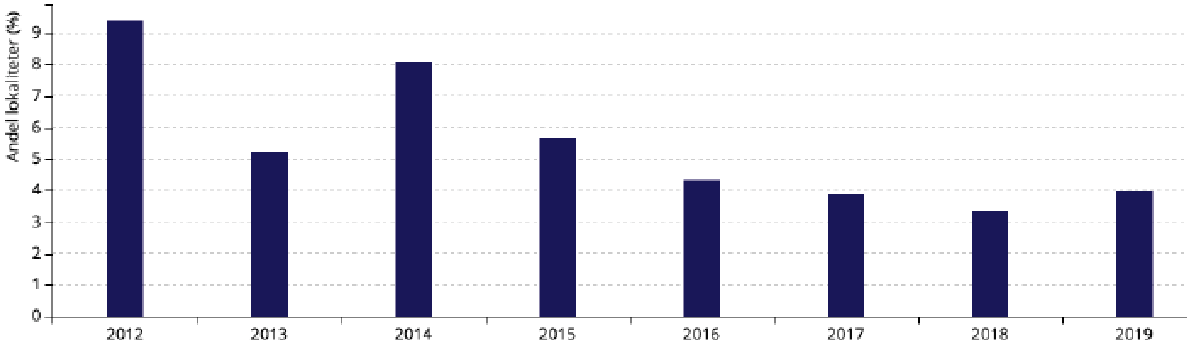

Figure 3.4. Percent share of farms with sea lice levels above limits set by the government (Source: Barentswatch and Abate et al, 2020)

However, the next question is if additional measures to reduce sea lice prevalence leads to an increase or reduction in production costs?

Figure 3.5 shows the development of inflation-adjusted unit production costs over time. We see that production costs were fairly stable until 2012, when the farm regulation of sea lice was introduced. Costs then increased until they reached a peak level of 32 NOK/kg in 2016. In the two years after 2016 – the first years with TLS – production costs declined, to 30 NOK per kg in 2018. One should be careful with the interpretation of this development, as other factors may have influenced costs, such as changes in input prices and biophysical shocks in the form of diseases, temperature changes, etc.

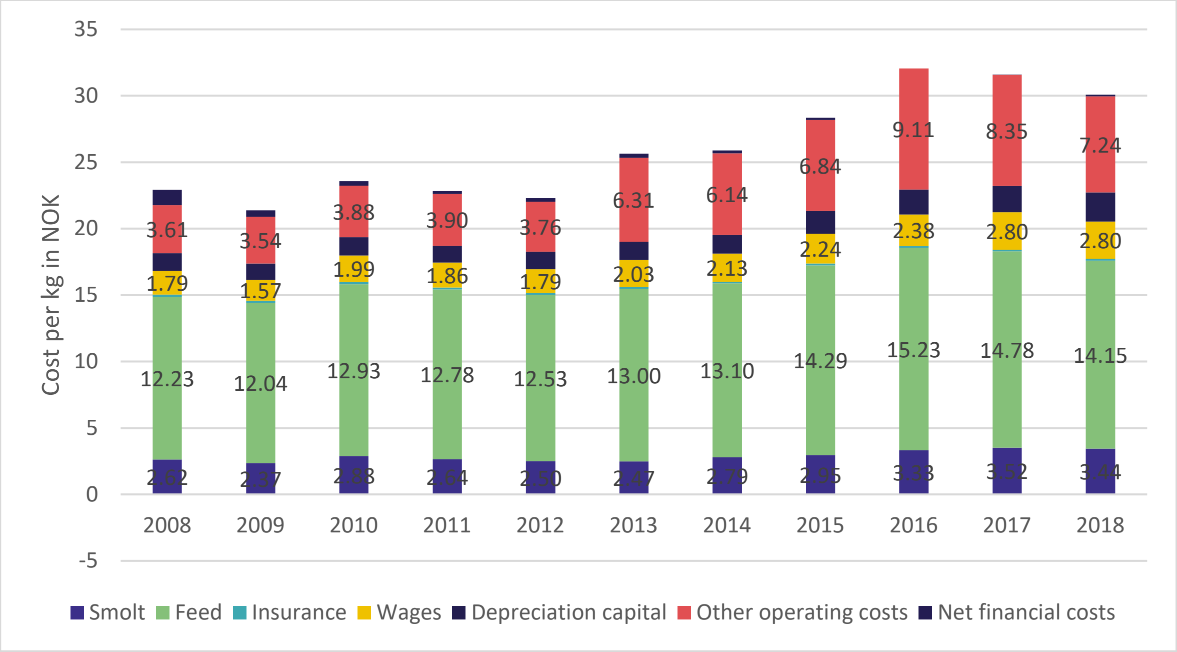

Figure 3.5. Development of inflation-adjusted production costs per kg fish produced over time (Source: Directorate of Fisheries and Abate et al, 2020)

4. Economic performance

4.1. Biological productivity performance

Norwegian salmon firms are restricted by a quota on maximum allowable biomass (MAB) of live fish in the sea at any time. Figure 4.1 shows the development of production per tonne of MAB over time since 2004, when the MAB regulation was introduced. Salmon aquaculture firms needed some years to learn how to adapt production to the MAB regulation, but in 2012 reached an average ratio of production in tonnes to MAB in tonnes of around 1.6-1.7. After that salmon firms have largely been able to sustain those ratios on average, but with some decline in the last two data years. Biological shocks in the form of diseases, sea lice etc. can reduce the production/MAB ratio. We see that each year there is substantial variation across firms as indicated by plus/minus standard deviation, again indicating the presence of biological shocks along the Norwegian coast which affect salmon firms unevenly.

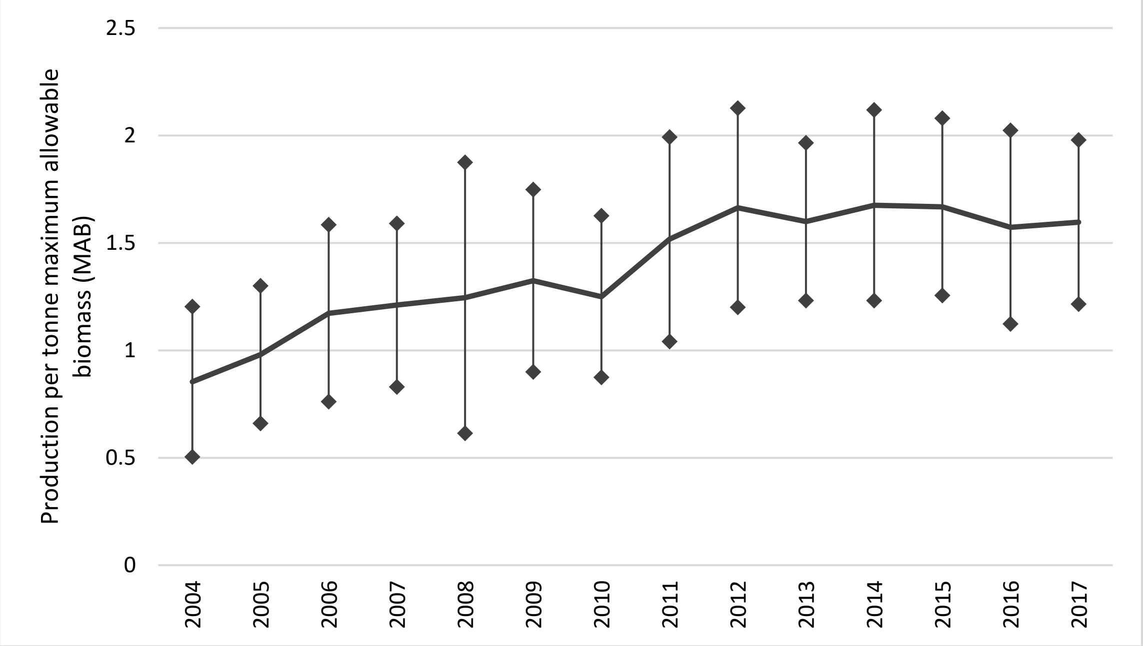

Figure 4.1. Average and st.deviation of salmon produced per tonne of maximum allowable biomass (MAB) of Norwegian salmon firms. The vertical lines represent +/- one st.dev. (Data source: Norwegian Directorate of Fisheries.)

The biological production process in salmon aquaculture is basically one of converting salmon feed into salmon biomass growth. Salmon feed typically represents 40-50% of production costs. Hence, a central productivity metric is the feed conversion rate (FCR), i.e. the ratio of salmon biomass growth to feed input volume. Figure 4.2 shows the development of the average feed conversion rate and its variability as measured by plus/minus one standard deviation. When production is efficient and devoid of diseases and other shocks that influence salmon growth and survival, FCR should be around one. We see here fluctuations in average FCR over time, indicating variations in biophysical shocks influencing biological productivity. Moreover, we see large FCR variation across firms each year as indicated by plus/minus one standard deviation of FCR, indicating the presence of biological shocks along the Norwegian coast which affect salmon firms unevenly.

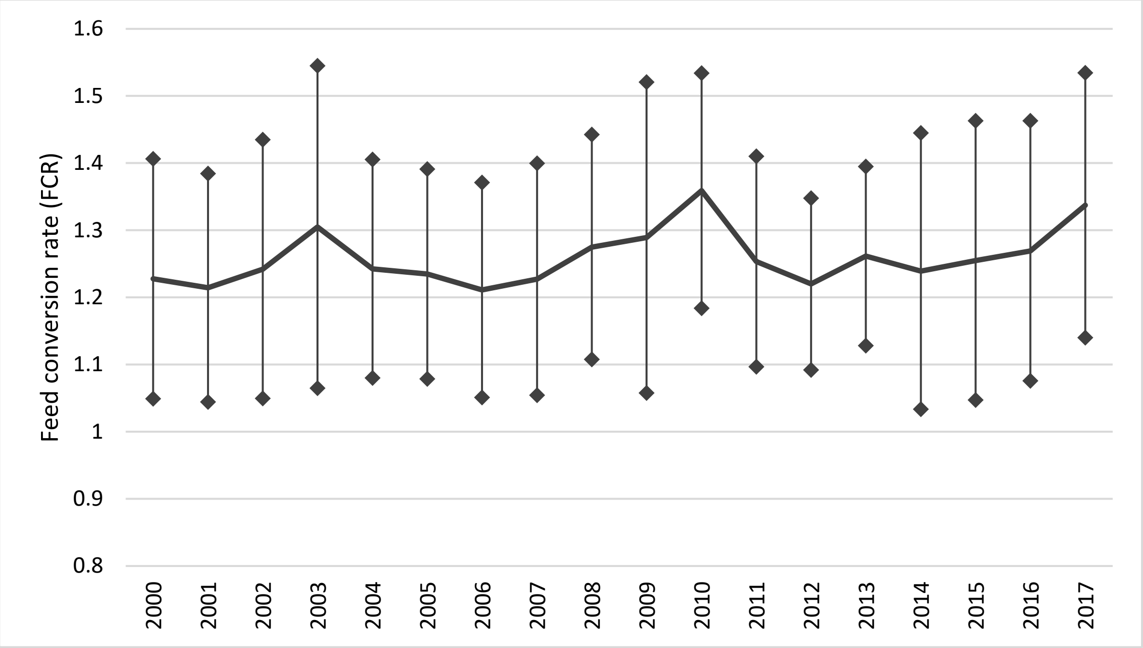

Figure 4.2. Average and st.dev. of feed conversion rate (FCR) of Norwegian salmon firms. Vertical lines represent +/- one st.dev. Data source: Norwegian Directorate of Fisheries

4.2. Production cost performance

In this section we examine the development of production costs. Figure 4.3 plots the average and standard deviation of inflation adjusted production cost per kg of salmon of Norwegian salmon firms participating in the survey of the Norwegian Directorate of Fisheries. This survey typically collects data from the majority of salmon firms each year. We see that after a decline of production costs from 2000 to 2005, costs have then increased. The variability of production costs as measured by the standard deviation have also increased, particularly in the last two years.

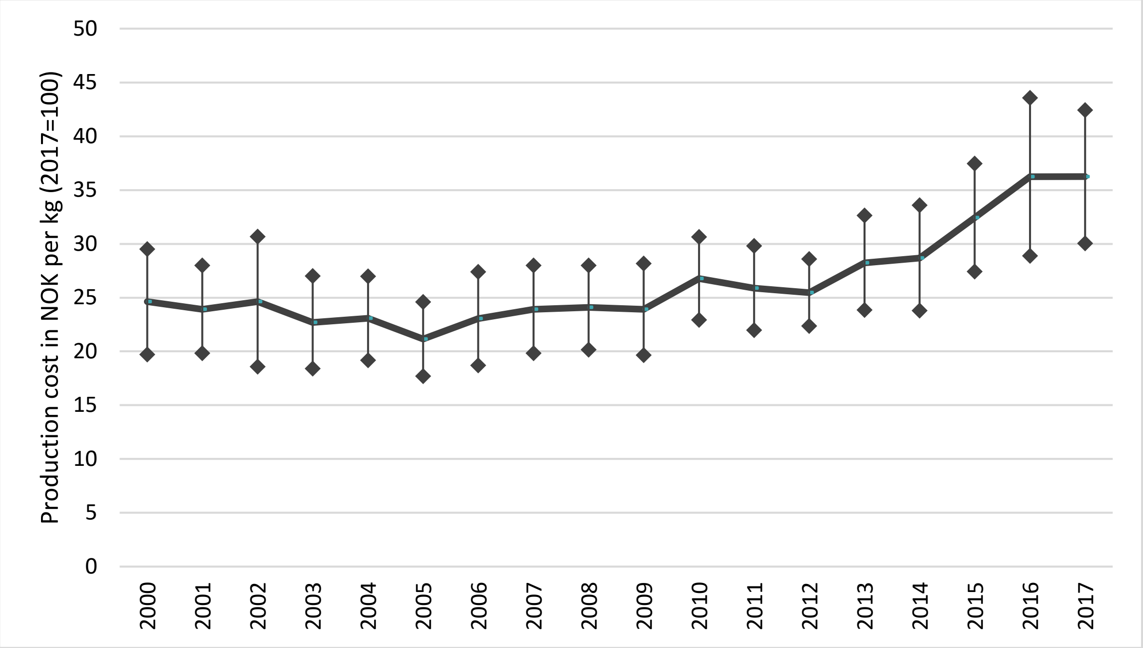

Figure 4.3. Average and st. deviation of inflation adjusted production cost per kg of salmon of Norwegian salmon firms. The vertical lines represent +/- one st.dev. Data source: Norwegian Directorate of Fisheries

Figure 4.4 shows the development in inflation adjusted production costs per kg from 2005 to 2017. It is based on firm level data, where firms have been sorted by their production costs. This is a sample of salmon firms representing the majority of total production. We have scaled up the production volume of firms in this sample so that the total volume is equal to total Norwegian salmon production in the respective years. Each year we see big differences in average production costs between low-cost producers and high-cost producers. A question is to what extent these cost differentials are caused by resource rents related to different biological conditions, or quasi rents related to technology, quality of management, government regulation etc. Another question is to what extent the relative cost performance of individual firms is stable due to more or less permanent rent differentials, or fluctuates due to shocks, e.g. biological shocks caused by diseases. In section three we will investigate this further.

Assuming that the sample is fairly representative each year we see that real production costs have shifted upwards from 2005 to 2017. Since the state of technology and skills have not declined, it is most reasonable to relate these upwards shifts to input prices increasing faster than inflation over time or increasing negative biological shocks (external effects) over time.

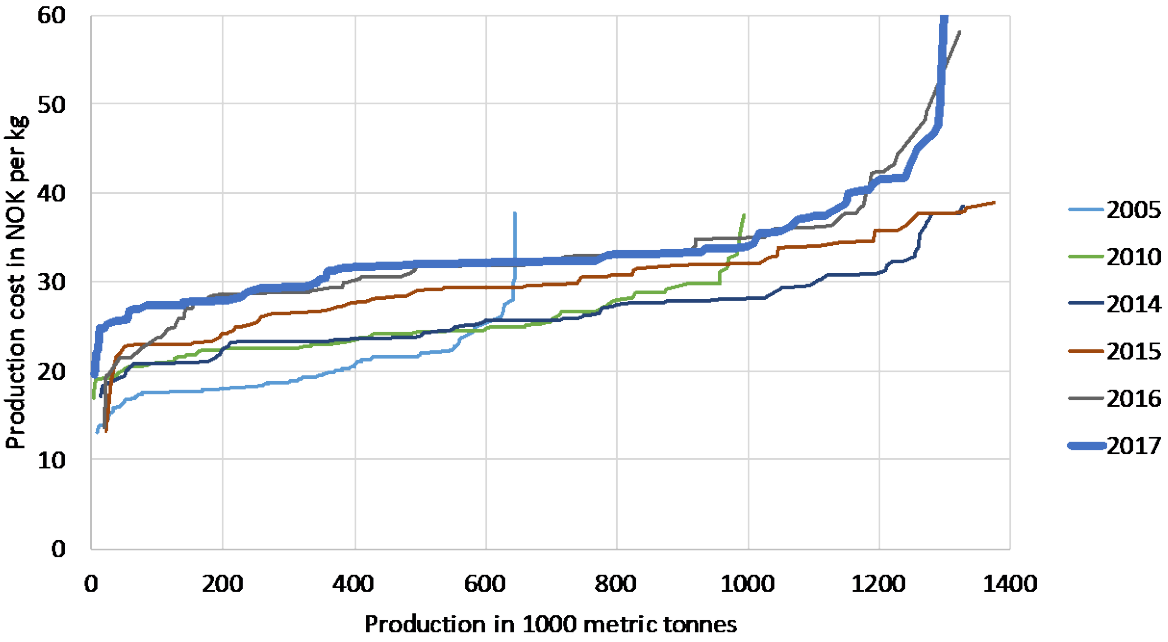

Figure 4.4. Development of production cost per kg 2005-2017. Inflation adjusted, 2017=100. (Data source: Norwegian Directorate of Fisheries)

4.3. Profitability of salmon firms

The profitability of salmon firms are functions of biological performance, technology and management, and prices of inputs and output. In other words, both production performance and market developments influence profitability.

Salmon farming companies in Norway have in recent years experienced high profit rates, as indicated by Figure 4.5. According to this figure average operating profits have fluctuated significantly over time, but in the best years have been high compared to private sector averages. We also observe the significant variation measured by the standard deviation in operating margins across firms within a single year, which may be due to differences in the quality of management and biophysical conditions and shocks (e.g. diseases).

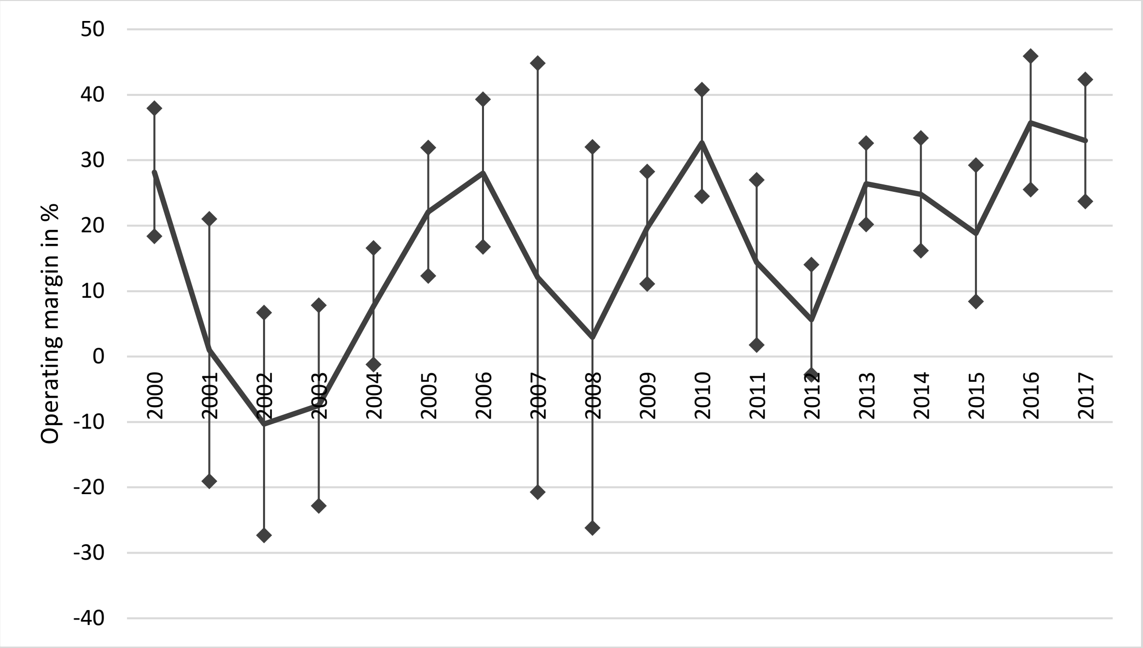

Figure 4.5. Average and st.deviation of operating margin of Norwegian salmon firms. The vertical lines represent +/- one st.dev. (Data source: Norwegian Directorate of Fisheries.)

The increase in production costs per kg and also the operating margin at the same time is consistent with a positive shift in global demand for salmon which dominates shifts in global supply (marginal costs), and also an inelasticity of global supply. Furthermore, it suggests that the salmon aquaculture sector do not respond to increased prices by increasing the supply of salmon. This may be caused by both biological problems and government regulations in producer countries.

Figure 4.6 shows the development of average and st.dev. of return of total capital (ROTC) of Norwegian salmon firms. We see the cyclicality of average ROTC over time. In 2002 and 2003 ROTC was negative. In some other years ROTC have also been below 10%, but we also see that in many years ROTC has been well above 10%.

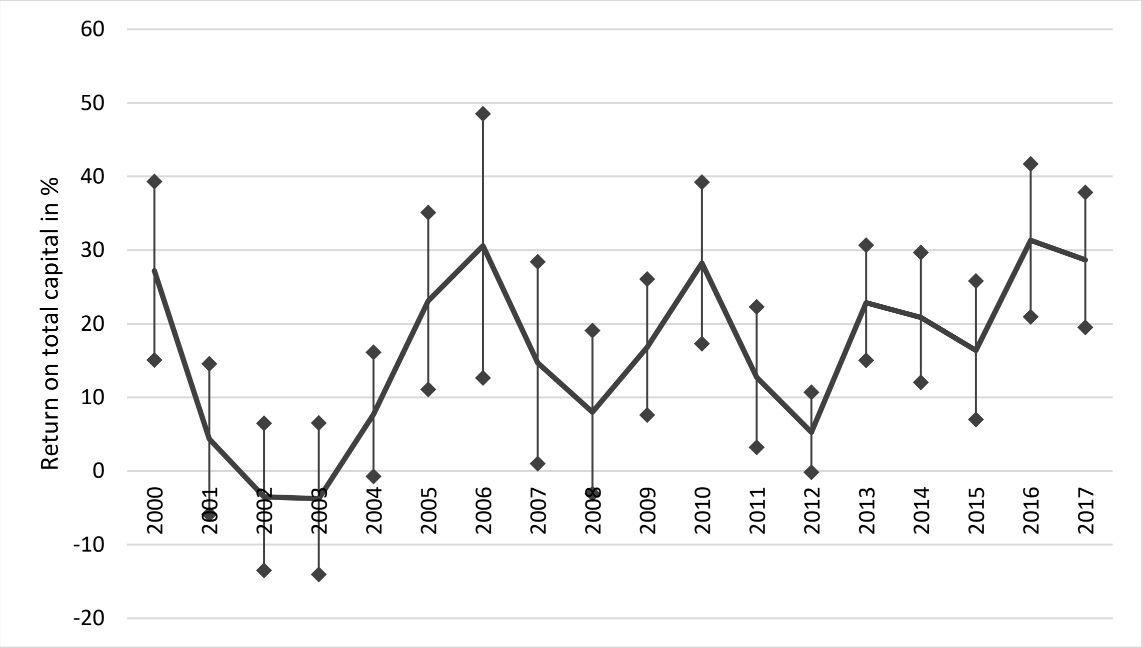

Figure 4.6. Average and st.dev. of return of total capital (ROTC) of Norwegian salmon firms. Vertical lines represent +/- one st.dev. (Data source: Norwegian Directorate of Fisheries.)

4.4. Variation in productive and economic/financial performance across firms

We have observed variation over time and across firms each year in the preceding sections. A question is to what extent the differences in productive and economic performance across firms each year is fairly stable over time, i.e. that there may be fairly stable relative Ricardian rents across firms. In order to investigate this we plot productivity and economic performance metrics for individual firms. We have done this for a subsample of 49 firms which are observed every year from 2009 to 2017. In figures 4.7-4.12 we provide for each firm an individual plot of the level and rank of (a) production per tonne of maximum allowable biomass (MAB), (b) production costs per kg, and (c) return on total capital (ROTC). Production per tonne of maximum allowable biomass (MAB), plotted in figures 4.7-4.8, is a measure of to what degree the firm is able to exploit its regulated production capacity constraint.

The overall picture that emerges is one of significant instability in productive and economic performance for each firm over time. Moreover, the time pattern of variation differs significantly across firms, indicating that they are subject to individual shocks to their productivity and economic performance at different points in time. From the figures we see that firms' ranking are typically highly unstable. It should also be noted that since we have omitted firms that are not observed all years 2009-2017 from this descriptive analysis, and some of these may have exited due to poor economic performance, we may underestimate the volatility of firms' relative performance. However, the implication is that we do not have relatively stable rents as in the Ricardian textbook examples. This is an industry with inherent biological shocks, and other shocks from markets and society, which leads to large shifts in firms' relative productive and profit performance ranking.

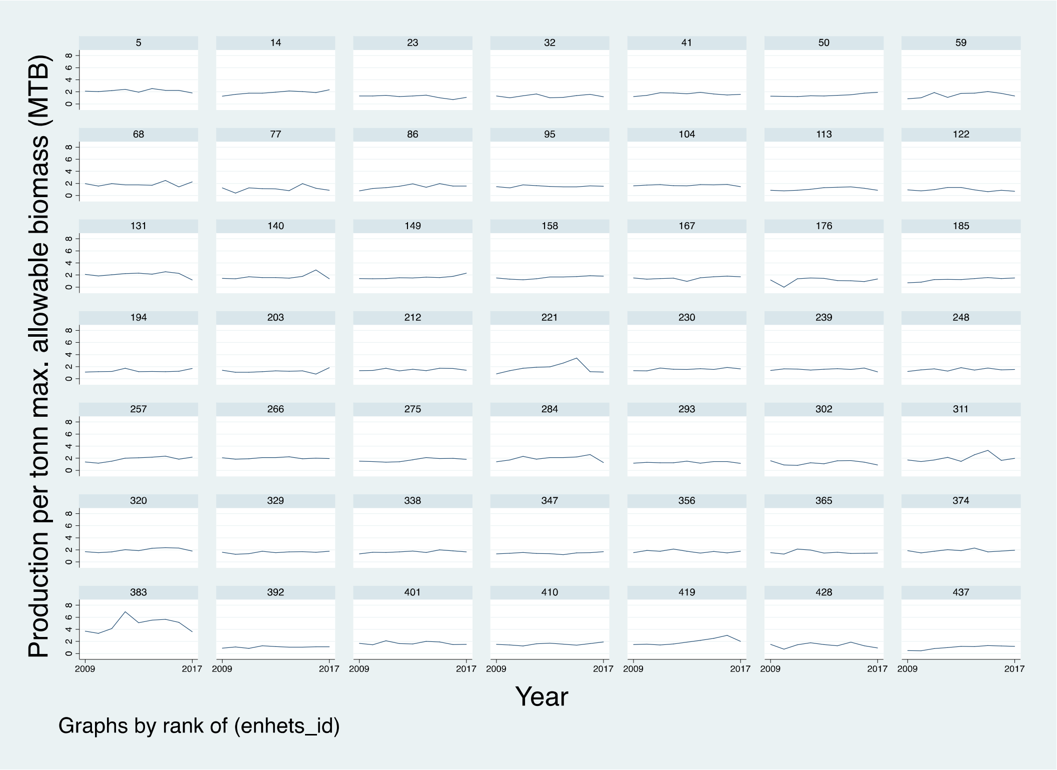

Figure 4.7. Production per tonne maximum allowable biomass for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

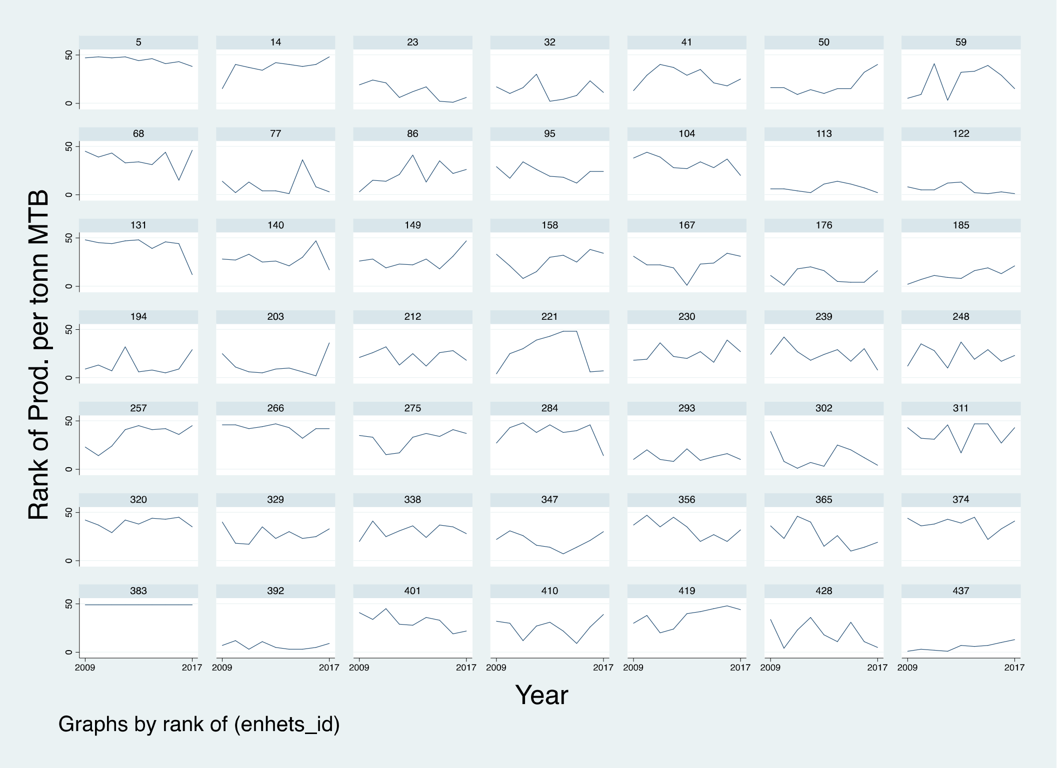

Figure 4.8. Firm ranking by production per tonne maximum allowable biomass for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

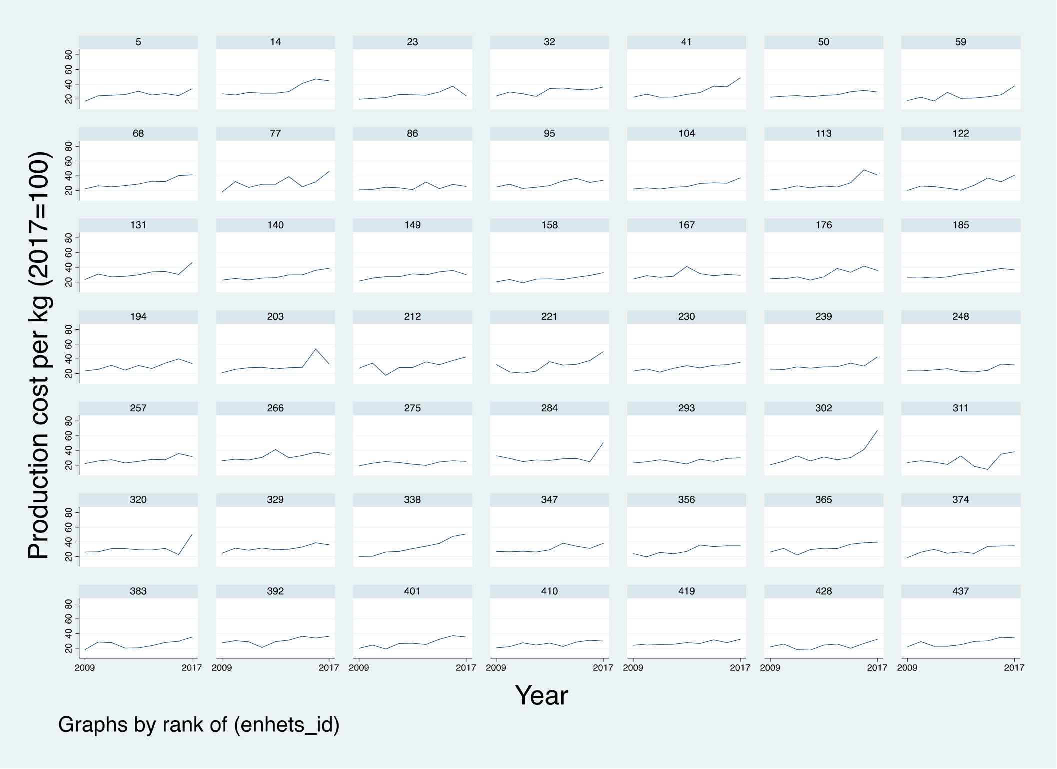

Figure 4.9. Production cost per kg for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

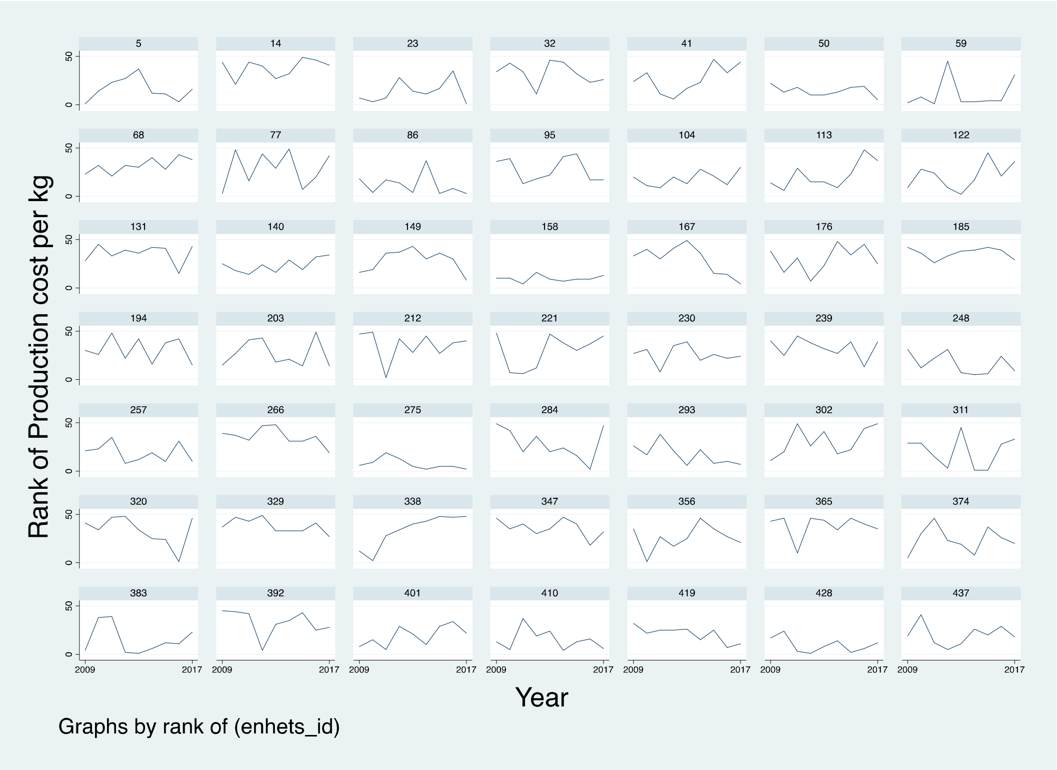

Figure 4.10. Firm ranking by production cost per kg for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

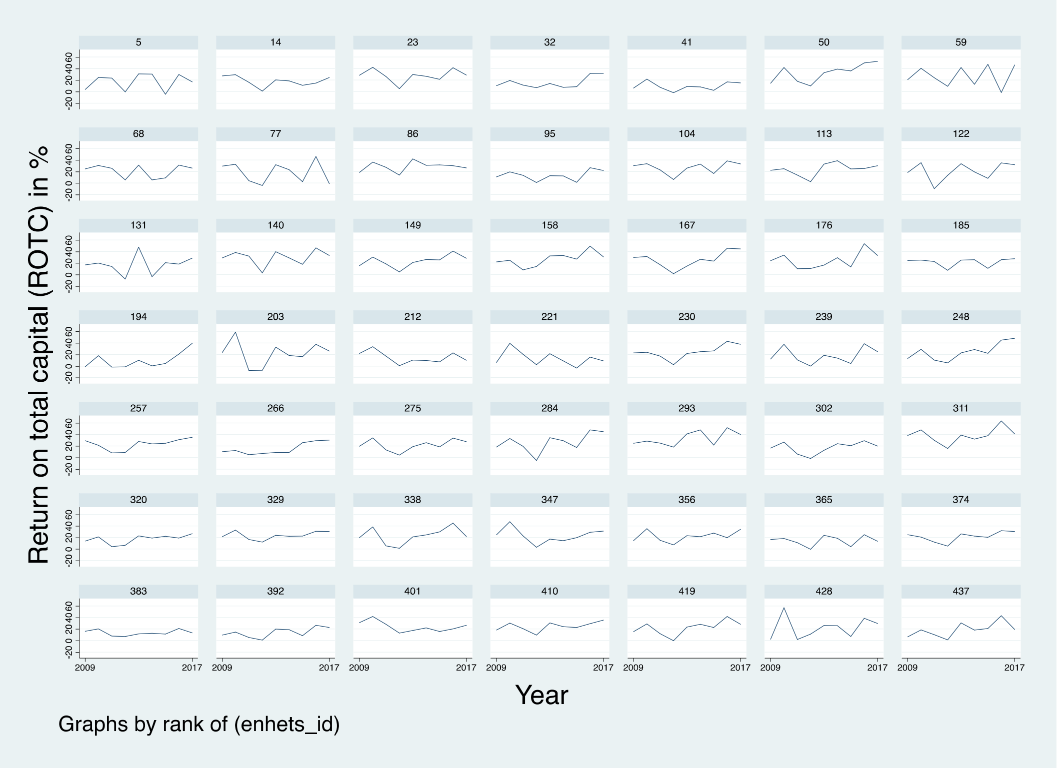

Figure 4.11. Return on total capital (ROTC) for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

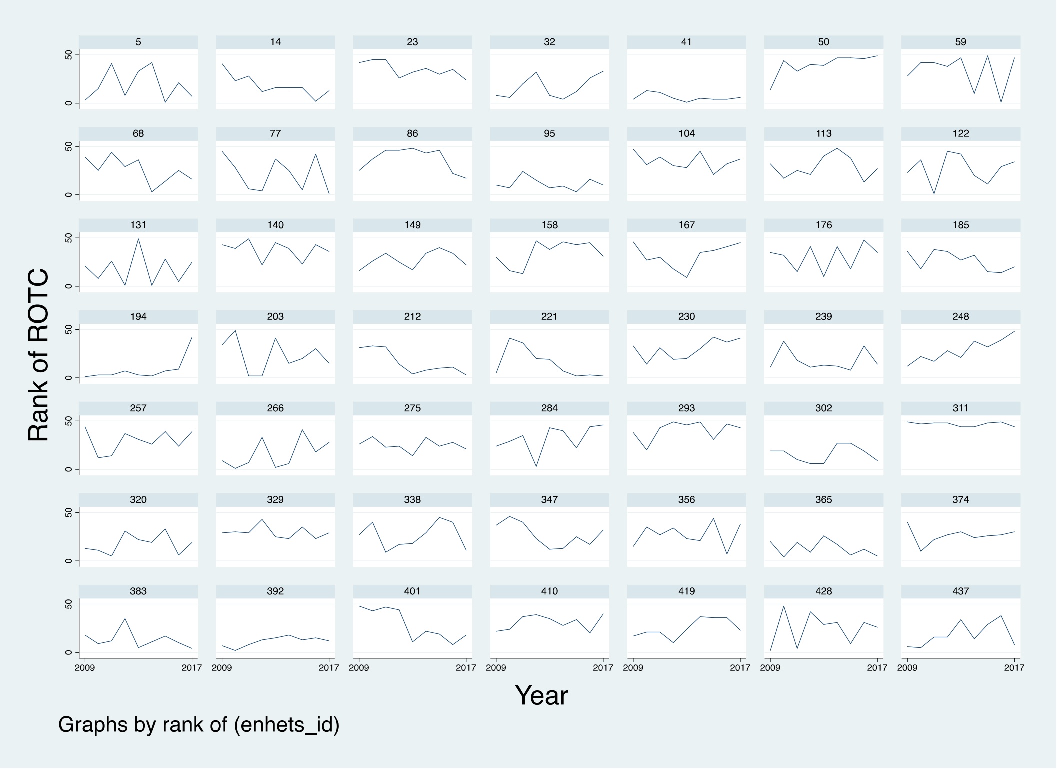

Figure 4.12. Firm ranking by return on total capital (ROTC) for 49 firms observed 2009-2017. (Data source: Norwegian Directorate of Fisheries.)

4.5. Taxation of aquaculture

Salmon aquaculture pays for the use of sea area. A production tax of 0.40 NOK per kg is introduced from 2021. Municipalities claim property tax for salmon farming sites based on the market value of the fixed capital equipment at the farm site. Firms also pay fees on their export of seafood to fund generic seafood marketing and a seafood sector R&D, where the rationale is to correct for market failures in investments in promotion of seafood products and aquaculture R&D.

Except for the above described fees and taxes salmon firms generally face the same tax regime as other private sector companies. They pay a revenue or profit tax with the same 22% tax rate as other private sector companies. Owners of salmon companies face a general wealth 0.85% tax on net wealth, i.e. gross wealth minus debt and a deductible. For owners of stocks in salmon companies listed on public stock exchanges the wealth is calculated as 80% of stock market value January 1st. For owners in non-listed companies the value is 80% of the company's taxable assets, where values of different assets must be estimated. These assets include the market value of the MAB licenses, a calculated value of live fish stock, harvested fish, feed stock, feed barges, etc.

A debate on the sharing of revenue from salmon aquaculture in Norway has emerged in recent years. There are different types of arguments. A central argument is that fish farming companies benefit economically from the use of coastal farm sites, which are public property. The farm sites provide access to 'free' inputs and appropriate conditions from the nature to the salmon production process in terms of e.g. sea water and topographical conditions. Farm sites are not bought by salmon farming companies, but they have been given an exclusive right for use of the location from society. It is argued that society should get a share of the profits from its farm locations with high bioproductivity. A fiscal argument is that government at different levels – municipalities, counties and central state – will need additional tax revenue in the future to fund a host of public services demanded by the public.

Next, if salmon aquaculture is a potential candidate for extraordinary taxation, one has to analyze the market structure to assess the opportunities for taxation which will not lead to significant deadweight losses compared to taxation alternatives. The salmon market is global and highly integrated in the sense that the price formation for farmed salmon is determined by global supply and demand, with different qualities receiving discounts or premiums relative to the global price. It is argued that appropriate sites for farming are limited or scarce, or that the supply of farmed salmon for other reasons is restricted. The main reason would be government regulations in producer countries limiting production. It is also argued that there is a resource rent – or differential rent – that can be captured through taxes from farm sites with different bioproductivity. It is argued that an appropriately designed extraordinary tax – also called resource rent tax - can provide tax revenue with limited economic efficiency losses for society, i.e. that it is possible to design a relatively neutral tax regime where aquaculture investment projects which are economically efficient for society to initiate will still be initiated by private investors when they have calculated after tax financial returns.

In Norway, the petroleum and hydropower sectors have created a precedent for a potential extraordinary tax on the salmon aquaculture sector. These sectors face additional taxes on income (or profit) and other taxes. The arguments are very similar to those presented above, i.e., that petroleum resources and water resources are public property, that they are sources of resource rents, and that it is possible to design taxes that are fairly neutral. Tax revenue from these two sectors represent a significant share of total tax revenue in Norway. However, the tax regimes are subject to debate regarding neutrality, and how e.g. non-neutrality lead to under-investments in hydropower plants.

4.6. International regulation and competitiveness

Salmon is produced in several countries with appropriate biophysical conditions for salmon aquaculture, broadly speaking sufficiently sheltered coastal zones and appropriate sea temperatures through the year. Salmon aquaculture technology and know-how is available globally through suppliers of capital equipment, feed, pharmaceuticals, and consultancy services, and through multinational salmon companies which operate in several countries. Salmon production volumes and growth rates have developed at different rates across countries. Figure 4.13 and 4.14 show the production volumes and production shares (in %) of Norway and other producer countries for Atlantic salmon.

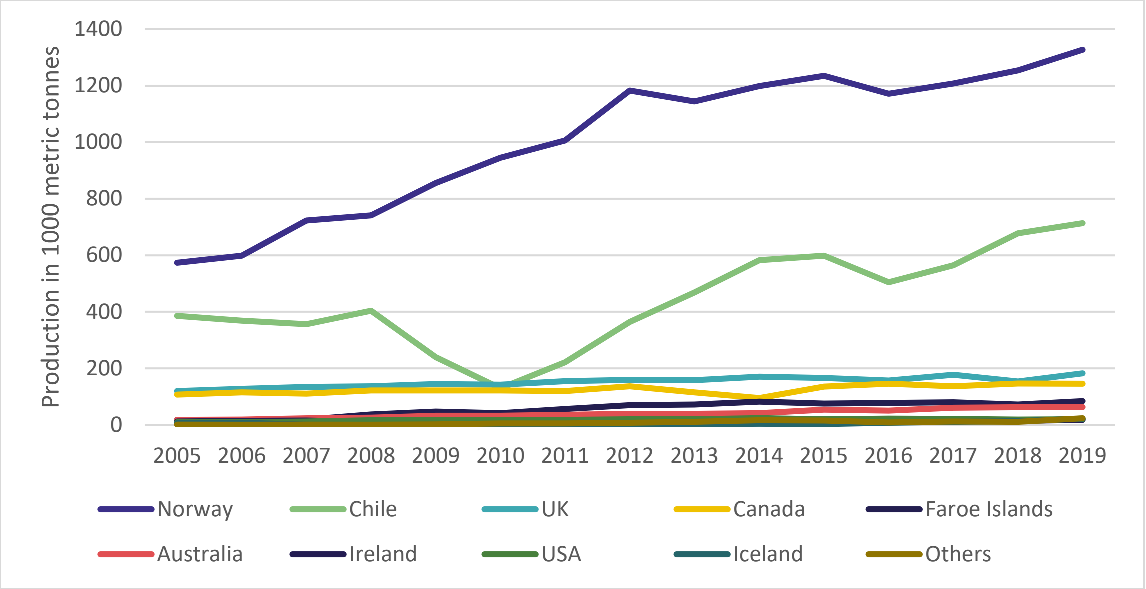

Figure 4.13. Production of Atlantic salmon by country (Source:Kontali)

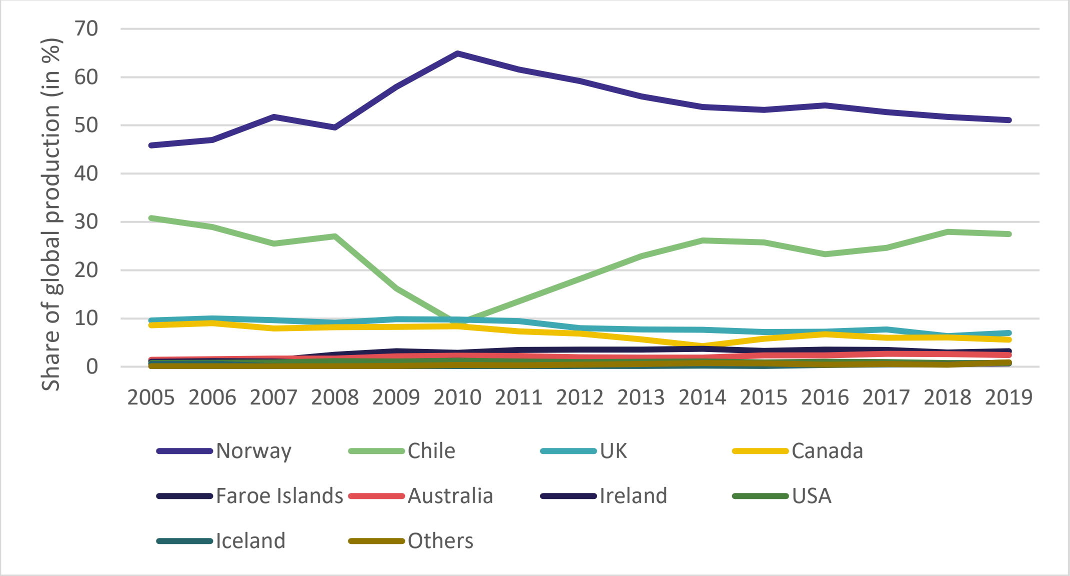

Figure 4.14. Atlantic salmon production shares in % by country (Source:Kontali)

Only to some extent can the development of production and shares be explained by different biophysical conditions across countries. Different regulatory regimes may have played a very significant role in explaining countries' different salmon aquaculture growth trajectories. Furthermore, it can be argued that it is possible to produce in a sustainable manner much larger volumes of salmon in some producer countries than we currently observe.

Salmon aquaculture is an example of a farmed species where different countries have found different balances between sustainability concerns and different implementation in terms of regulatory measures (Osmundsen, Almklov and Tveterås, 2017). The salmon aquaculture sector in different countries face similar biological risks and externalities. However, government measures designed to mitigate externalities differ significantly. The policy measures implemented in the main salmon producer countries have also been motivated by other policy objectives, which again have been influenced by the political power of different stakeholders. Policy measures aimed to mitigate externalities, or the absence thereof, have had significant effects on the development of production in salmon producer countries. For the United Kingdom (UK), Canada, and the United States (US), strict regulations may have led to lower environmentally sustainable growth than could have been possible, depending on the interpretation and balancing of sustainability concerns (Osmundsen, Almklov and Tveterås, 2017). In the more liberally regulated Chilean sector, the absence of proper regulations has led to a disease-driven decline in production since 2008 that could have been avoided (Asche, Hansen, Tveteras, & Tveteras, 2009).

Although salmon may end up as differentiated final consumer products and meals, exported farmed salmon products can be characterized as a commodity as it is difficult to differentiate the attributes of whole salmon or salmon fillets for companies and countries. Salmon farming companies in different countries compete in many export markets, and the price formation is global. What emerges is that the supplied quantity and market shares of salmon from different companies and countries is determined by government regulations limiting production, and firms' productivity and cost efficiency which is largely determined by their biological performance and government regulations.

Regulations which influence productions costs and profits for particular locations or technologies can have effects through different mechanisms: (1) Location of investments and production in Norway and other producer countries, (2) investments in aquaculture plants on land, in the coastal zone and offshore, (3) investments in alternative technologies with different environmental effects, (4) vertical and horizontal organization of value chains through e.g. mergers and acquisitions, (5) economic geography of production activities in salmon value chain within Norway.

One can argue that further sustainable and internationally competitive growth in Norwegian salmon production is possible the next decades with a properly designed policy regime. This should include regulation of production and environmental externalities that provides sufficient incentives to investments in innovation and plants at different stages of the value chain.

5. A bioeconomic model of externalities

Here we propose a bioeconomic model of salmon farming with farms using a common-pool resource, such as a fiord, and where there are negative externalities in the form of fish diseases and sea lice.

The model can be used to specify heterogeneous farm sites with different characteristics in terms of carrying capacity and exposure to diseases and sea lice from other farms sites. It can be employed to evaluate the effects of different regulations on farm production, productivity and profits. Furthermore, it can be used to analyze different regulations with different levels of regional biomass etc. Hence, it can give predictions on how regulations influence producer behavior and social welfare. The model can be useful in understanding the economic gains from regulation when firms do not internalize the externalities in their decision-making process.

The model has profit maximizing ‘upstream’ farm(s) and ‘downstream’ farm(s), where the upstream farms have negative external effects on the downstream farms, caused by hydrodynamic processes that carry diseases and sea lice from upstream to downstream farms. The model builds on previous research on salmon epidemiology and bioeconomics (Groner et al, 2016; Abolofia et al, 2017; Arriagada et al, 2017; Aldrin et al, 2019; Kragesteen et al., 2019; Overton et al, 2019; Samsing et al, 2019; Dresdner et al, 2019).

The model can be used to analyze how externalities affect the performance of farms. Furthermore, the model can demonstrate, depending on parameter values, that when upstream farms maximize their profits without regard for effects on downstream farms profits through disease and sea lice externalities there is an economic efficiency loss. In particular, it is possible to analyze the choices when external effects are fully internalized by farms, i.e. when total profits of all farms are maximized jointly.

Farms’ choice variables are (1) the number of smolts released into the salmon pens, and (2) costly disease and sea lice mitigation efforts. The sea lice mitigation efforts are divided into preventive and curative mitigation efforts. Sea lice mitigation efforts reduce the number of sea lice at the farm and thus contribute to reduced mortality. But the curative treatments also have a negative side-effect on salmon mortality because they cause stress and harm to salmon being treated, while the preventive efforts do not have any negative effects on mortality.

Farms face constraints on maximum allowable biomass (MAB, in Norwegian; MTB) of salmon in the cages, and the maximum number of sea lice per salmon. The MAB restriction can typically be related to the carrying capacity of the farm site. The sea lice regulation can be motivated by a desire to limit negative externalities to other farms and to stocks of wild salmonid fish.

5.1. Profit maximization

The firm maximizes the following profit function:

$$\pi = P_Y B - (P_S S + P_F BFF(Y + Y_F) + P_O(Y + Y_F) + P_D X_D + P_{LP} X_{LP} + P_{LC} X_{LC} + \left(\frac{K}{K_L}\right) + Kr)$$

π = profits, P_Y = price of salmon (NOK per kg), *B* = harvested biomass of salmon (in kg), P_S = price of smolt (NOK per individual), *S* = number of smolts released into pens, P_F = price of feed (NOK per kg), *BFF* = biological feed factor (kg of feed per kg of salmon growth), *Y* = production of salmon (in kg), Y_F = salmon biomass which have been fed but died before harvesting time (in kg), P_O = other production related operating costs, P_D = price of disease treatment per unit of treatment, X_D = treatment of diseases (in units) P_{LP} = price of preventive lice treatment per unit of treatment, X_{LP} = Preventive sea lice mitigation effort (in units), P_{LC} = price of curative lice treatment per unit of treatment, X_{LC} = curative sea lice mitigation effort of farm (in units), *K* = capital invested in fixed capital equipment (in NOK), K_L = average life of capital equipment (in years), *r* = cost of capital (in %).

The firm's choice variables are number of smolts released (*S*), and units of treatment with respect to disease and lice (X_D, X_{LP} and X_{LC}), all constrained to nonnegative values.

The biomass in the cages (B) at harvest has to be less than or equal to the maximum allowable biomass (MAB, MTB in Norwegian) set by the government. One can assume that the MAB is determined by the carrying capacity of the farm site.

5.2. Biological relationships in the model

This section presents biological functions influencing the mortality and growth of salmon.

Mortality rate

The mortality rate of the salmon is decomposed into three components:

$$M = M_I + M_D + M_L,$$

where M_I = intrinsic mortality rate due to other causes than external disease and sea lice pressure, M_D = mortality rate related to disease pressure caused by number of smolts in own and upstream farms, and M_L = mortality rate related to sea lice pressure from neighbor farms.

Disease mortality rate

The mortality rate related to disease pressure caused by number of smolts in own and upstream farms is given by:

$$M_D = (F_{D1}\cdot(S/S_T)^{bD1} + F_{D2}\cdot((S/S_T)^2)^{bD2} + F_{DN}\cdot S_N^{bDN})/(A_D\cdot X_{DN}^{xDN}\cdot X_D^{xD})$$

where S_T = treshold number of smolts at own farm location for which disease pressure increases, F_{D1} = first order disease pressure factor from own farms related to ratio between number of smolts released and treshold smolt value, b_{D1} = first order elasticity effect of disease pressure factor from own farms related to ratio between number of smolts released and threshold smolt value, F_{D2} = Second order disease pressure factor from own farms related to ratio between number of smolts released and threshold smolt value, b_{D2} = Second order elasticity effect of disease pressure factor from own farms related to ratio between number of smolts released and threshold smolt value, F_{DN} = disease pressure factor from neighbor farms related to number of smolts (can be related to distance), S_N = number of smolts released into neighbor farms, b_{DN} = elasticity of effect on disease of smolts released into neighbour farms, X_{DN} = disease mitigation effort of neighbor farms, and X_D = disease mitigation effort of farm, A_D = State of technology of disease mitigation effort function, x_{DN} = elasticity of disease mitigation effort of neighbor farms, x_D = elasticity of disease mitigation effort of farm.

The numerator of the mortality function has a component related to the number of smolts in downstream farm ($F_{D1}\cdot(S/S_T)^{bD1} + F_{D2}\cdot((S/S_T)^2)^{bD2}$), and a component related to the number of smolts in neighbor upstream farms ($F_{DN}\cdot S_N^{bDN}$). For own (downstream) farm the functional specification is such that with appropriate parameter values it allows the mortality rate to increase rapidly when the number of smolts increase beyond the treshold number of smolts (S_T). Hence, production can be constrained at the farm even without a government regulation on maximum allowable biomass (MAB).

The disease mitigation technology is given by the function $A_D\cdot X_{DN}^{xDN}\cdot X_D^{xD}$. It is a Cobb-Douglas function, where returns to scale of the disease treatment is $x_{DN} + x_D$. Innovations in the disease mitigation technology can be represented by the changes in the parameters A_D, x_{DN}, x_D. Higher values of these parameters will lead to lower disease induced mortality for given levels of mitigation effort variables X_{DN} and X_D.

Sea lice population and mortality model

Number of sea lice at farm, has two components, (1) number of sea lice at farm when sea lice mitigation effort function is equal to one, and (2) sea lice mitigation effort function:

$$\mathrm{N_L = ((S_L + F_L\cdot N_{LN}^{bLN})\cdot S^{bL}) / (A_L\cdot X_{LP}^{xLp}\cdot X_{LC}^{xLc})},$$

where $\mathrm{S_L}$ = external “natural” sea lice pressure factor (biophysical conditions influencing the natural exogenous prevalence of sea lice), F_L = Effect of number of sea lice at neighbor farms on sea lice multiplier (can be determined by geographic distance and hydrodynamic conditions), N_{LN} = Number of sea lice at neighbor farms, b_{LN} = elasticity of number of sea lice with respect to number of sea lice at neighbor farm(s), S = number of smolts released into the cages, b_L = elasticity of number of sea lice with respect to number of smolts at farm, A_L = state of technology (neutral technology component) of sea lice mitigation effort function, X_{LP} = Preventive sea lice mitigation effort (treatment) of farm, x_{Lp} = Elasticity of preventive sea lice mitigation effort of farm, X_{LC} = Curative sea lice mitigation effort (treatment) of farm, x_{Lc} = Elasticity of curative sea lice mitigation effort of farm.

The upstream farm always faces an exogenously given number of sea lice from neighbor farms (N_{LN}), while the downstream farm faces a number of sea lice that is determined by the individual profit maximization of the upstream farm, or the joint maximization of downstream and upstream profits.

The sea lice mitigation technology is given by the function $A_L \cdot X_{LP}^{xLp} \cdot X_{LC}^{xLc}$. It is a Cobb-Douglas function where returns to scale of the sea lice treatment is $x_{Lp} + x_{Lc}$. Innovations in the sea lice mitigation technology can be represented by the changes in the parameters A_L, x_{Lp}, x_{Lc}. Higher values of these parameters will lead to lower sea lice induced mortality for given levels of mitigation effort variables X_{LP} and X_{LC}.

Salmon mortality rate due to sea lice is determined by two components – (1) the ratio of sea lice to smolts and (2) the number of curative treatments (hence we assume that preventive treatments have no effect on salmon mortality):

$$M_L = M_{nls} \cdot (NL/S)^{bNLS} + m_{lc} \cdot X_{LC}^{xmLc},$$

where M_{nls} = coefficient of sea lice to smolts ratio (NL/S) in sea lice mortality function, b_{NLS} = elasticity of sea lice-to-smolts ratio (NL/S) in sea lice mortality function, m_{lc} = coefficient of number of curative treatments in sea lice mortality function, X_{LC} = curative sea lice mitigation effort (treatment) of farm, x_{mLC} = elasticity of number of curative treatments in sea lice mortality function.

Harvest biomass and production

The number of salmon at harvest time is $S \cdot (1\text{-}M)$.

Biomass at harvest, including all causes of mortality (in tonnes) is given by:

$$B = S \cdot (1\text{-}M) \cdot (W_S \cdot G).$$

Production is equal to biomass at harvest time less biomass of smolt released:

$$Y = B - S \cdot W_S$$

Biological and economic feed factor

We distinguish between biological and economic feed factor. For fish fed that die before harvesting we assume that average weight of dead fish is half of slaughter weight:

$$Y_F = M \cdot S \cdot ((W_S \cdot G)/2).$$

The economic feed factor (EFF) is equal to the feed use per kg of biomass produced by harvest time plus feed use for fish that died before harvesting, divided by production:

$$EFF = BFF \cdot (Y + Y_F)/Y.$$

5.3. Analysis of bioeconomic performance of farms

In the following we will analyze the bioeconomic performance of upstream and downstream farms with and without collaboration. First, we analyze decisions and outcomes when the upstream and downstream farm maximize their own individual profits, and where the downstream farm's profit maximization is conditional on the upstream farm's optimal decisions. Finally, we analyze choices and outcomes when the joint profits of upstream and downstream farm are maximized.

The following influence the economic costs of disease externalities in our model from the upstream to the downstream farm:

(a) The influence of the upstream farm on disease related mortality through ($F_D \cdot S_N^{bD}$).
(b) The disease mitigation efforts X_{DN} and X_D and its effect on mortality rate through the disease mitigation function $A_D \cdot X_{DN}^{xDN} \cdot X_D^{xD}$.
(c) The price of disease treatment per unit of treatment (P_D).

The following influence the economic costs of sea lice externalities in our model from the upstream to the downstream farm:

(a) The impact of lice pressure from upstream farms ($F_L \cdot N_{LN}^{bLN}$) on the number of sea lice.
(b) The sea lice mitigation efforts X_{LP} and X_{LC} and their effects on the number of sea lice through the mitigation function ($A_L \cdot X_{LP}^{xLp} \cdot X_{LC}^{xLc}$).
(c) The price of preventive and curative sea lice mitigation efforts, P_{LP} and P_{LC}.
(d) The effect of sea lice-to-smolts ratio (NL/S) on sea lice mortality.
(e) The negative effect of curative sea lice treatments (X_{LC}) on sea lice mortality through the component ($m_{lc} \cdot X_{LC}^{xmLc}$).

Choices and economic performance with individual and joint profit maximization

In the following we provide a numerical analysis for different sea lice restrictions. The sea lice restrictions can be set by government to limit negative externalities to stocks of wild salmonid fish. We choose typical prices for salmon and inputs such as feed and smolt. All parameter values are available in an Appendix.

We analyze input choices and outcomes in terms of profits, costs and externalities when salmon firms maximize individual profits and when they maximize joint profits. Profit maximizing firms will not internalize external effects of their production activities unless they are regulated by government or have economic incentives to do so. Joint profit maximization can be the result of government regulation that constrain externalities to appropriate levels or provide incentives to firm collaboration where all firms obtain the same or higher profits as with individual profit maximization.

Figure 5.1 shows how a transition from individual profit maximization to joint profit maximization changes relative input (or effort) use for downstream and upstream farms. When the index value is less than 100 the input use is reduced and when it is above 100 input use is increased. The sea lice restriction per fish is set at four different levels: 0.3, 0.4, 0.5 and 0.6 sea lice per fish. We see that the upstream farm generally increases its disease mitigation and sea lice mitigation efforts. On the other hand, the downstream farm reduces its disease mitigation and sea lice mitigation efforts, caused by reduced negative externalities from the upstream farm.

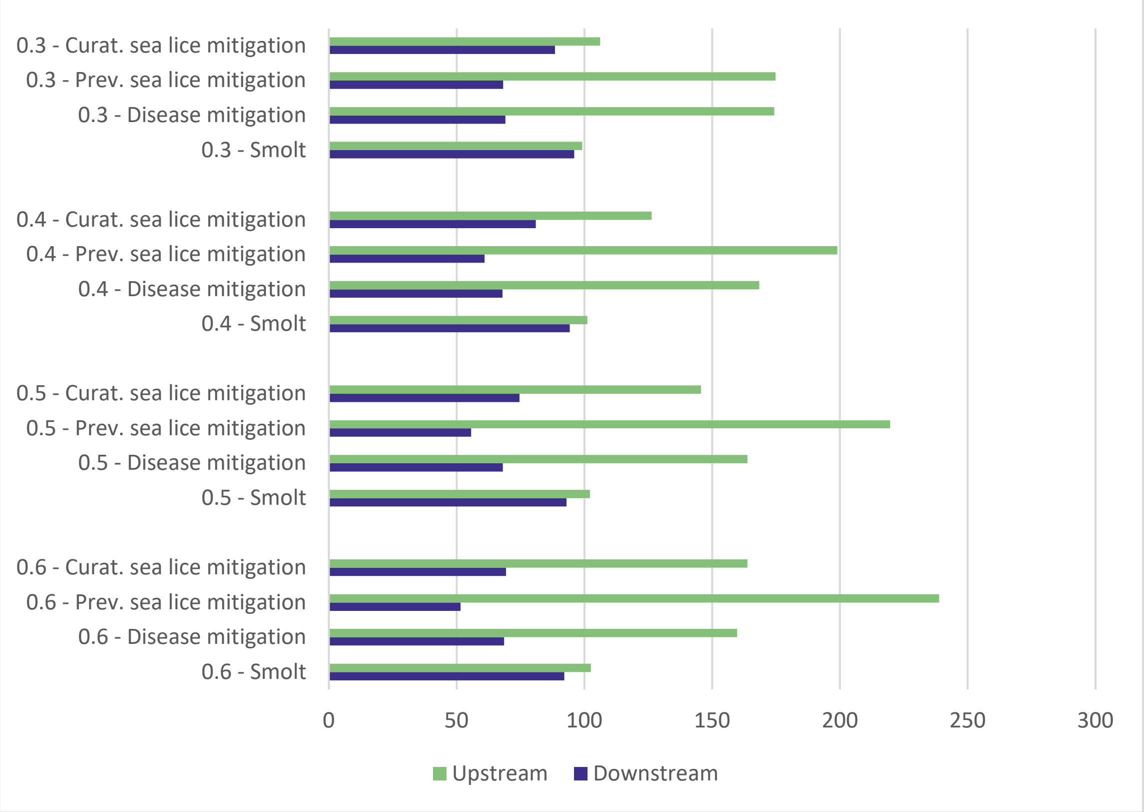

Figure 5.1. Ratio of input (or effort) levels with joint profit maximization to individual profit maximization for different sea lice restrictions

Figure 5.2 shows how transition from individual profit maximization to joint profit maximization changes relative production cost per kg of salmon for downstream and upstream farms. When the index value is less than 100 the cost per kg is reduced and when is above 100 cost per kg is increased. As before this is shown for four different sea lice restriction levels: 0.3, 0.4, 0.5 and 0.6 sea lice per fish. We see that the upstream farm generally increases its production cost per kg while the downstream farm reduces its cost per kg, caused by reduced negative externalities from the upstream farm and lower costs associated with mitigating the externalities.

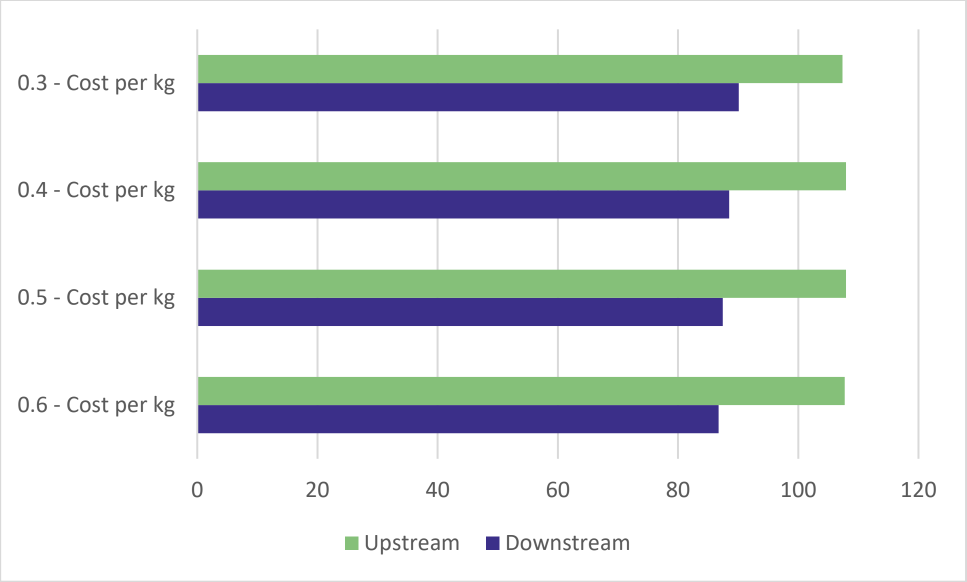

Figure 5.2. Ratio of production cost per kg of salmon with joint profit maximization to individual profit maximization for different sea lice restrictions

Finally, Figure 5.3 shows how transition from individual profit maximization to joint profit maximization affects total profits and individual profits for downstream and upstream farms for the four different sea lice restriction levels. We see that total profits increase in all cases, and also individual profit of the downstream farm increase. On the other hand, for the upstream farm profits are reduced, as it has higher disease and sea lice mitigation costs. In order to realize a higher joint profit, it is therefore necessary for the downstream farm to compensate the upstream farm so that its profits are not reduced.

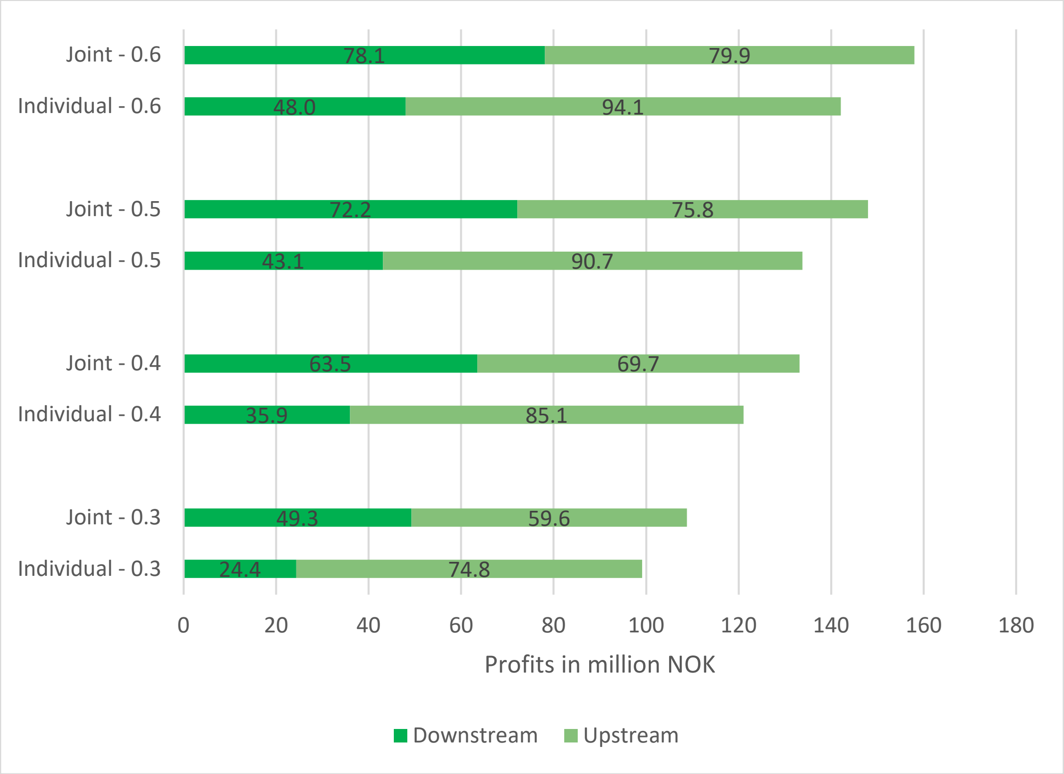

Figure 5.3. Profits with individual and joint profit maximization for different sea lice restriction levels

An implicit assumption here is that the farms have perfect knowledge about the sea lice and disease externalities specified in the model. In reality, neighbor farms may understand the qualitative nature of externalities between them, but do not have a quantitative empirical model of externalities and quantitative estimates of how mitigation measures influence externalities. This reduces the likelihood of the emergence of collaboration that can increase productivity and profits.

If voluntary or semi-voluntary collaboration do not lead to an equilibrium that maximizes welfare (here: profits) then government regulations which leads to optimal input choices and disease mitigation measures is an alternative. These regulations can include "emission quotas" for sea lice and disease pressure. But again, appropriate quantitative regulations depend on quantitative empirical models of externalities and how mitigation measures influence them.

6. Econometric analyses of salmon aquaculture economic performance and regulation

This section provides econometric analyses of economic performance of salmon aquaculture firms in relation to the regulation of maximum allowable biomass (MAB) and sea lice regulation. These analyses have been further documented in working papers by Asche, Rocha Aponte and Tveterås (2020) and Abate, Belay and Tveterås (2020).

6.1. MAB regulation and economic performance

In this section we analyze the effects of the maximum allowable biomass (MAB) regulation on cost productivity, primarily based on econometric results of Asche, Rocha Aponte and Tveterås (2020).

The findings are based on a translog variable cost function estimated using a Bayesian Seemingly Unrelated Regression System approach on salmon firm data from the Directorate of Fisheries' profitability survey for the years 2005-2014 (Asche, Rocha Aponte and Tveterås, 2020).

In 2004 a biomass-based license system was introduced where the MAB limits the amount of fish (in weight) that a producer can have in the pens at any time. A standard license is allowed to have 780 tonnes MAB. Licenses located in the northern regions of Troms and Finnmark were given a higher limit of 900 tonnes due to less favorable conditions for farming as lower temperatures reduce growth rates, later increases further to 945 tonnes.

Figure 6.1 shows the expansion ray for the MAB elasticity, i.e. relationship between production level and MAB (In Norwegian "MTB") elasticity. The shadow region represent the 95% credible interval centered at mean values. As expected, the effect diminishes as production levels increase. The curve of the expansion ray shows that cost increases generated by the MAB system are mainly due to unexploited economies of scale as the effect drastically falls as it approaches the optimal production point, with the effect wearing off completely at a production levels between 30 and 40 thousand tonnes. From the expansion ray, we can infer that, compared to the long-run optimal level, small firms face between 9% and 5% higher production costs; medium firms face between 5% and 2% higher costs and big firms face up to 2% higher costs.

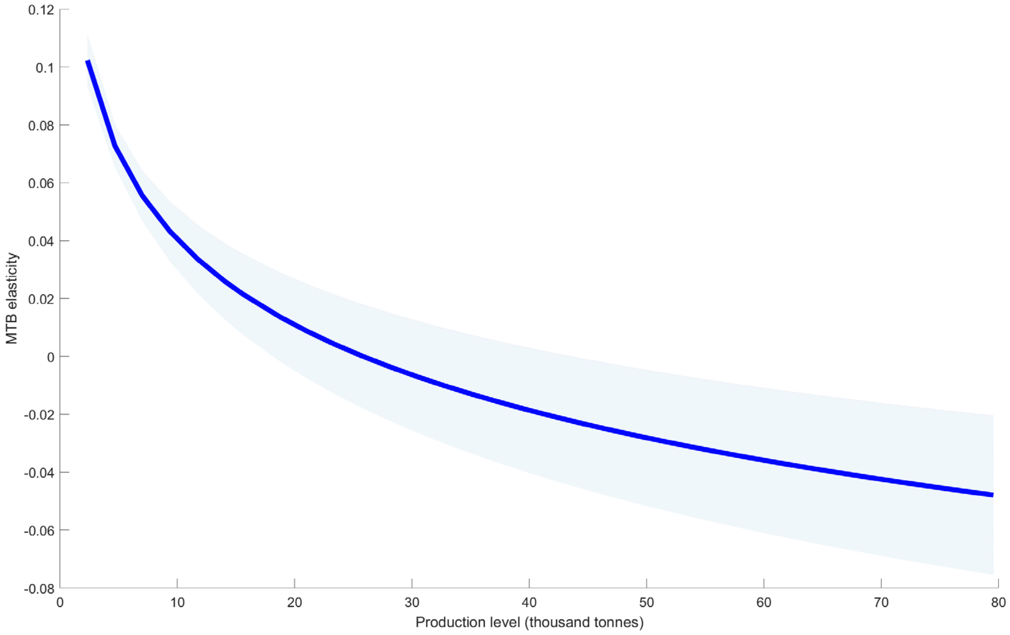

Figure 6.1. Relationship between production level and MAB (In Norwegian "MTB") elasticity. (Source: Asche, Rocha Aponte and Tveterås, 2020)

6.2. Econometric analysis of relationships between sea lice and firms' costs and profits

In this section we analyse relationships between salmon aquaculture firms' costs and profits and sea lice at farms. We estimate both econometric cost and profit functions (Abate, Belay and Tveterås, 2020).

6.2.1. Profit function specification

A firm's restricted profit function can be written as $\pi^V = \pi^V(p, w; z, t)$, where *p* is a vector of output prices, *w* is a vector of input prices, *z* is a vector of quantity of external effects (e.g. sea lice), and *t* is a vector of time dummy variables.

The shadow value of an external effect is is $SV_{\pi z} = \partial\pi^V/\partial z$, which measures the profit change for a one unit increase in the external effect *z*. A positive $SV_{\pi z}$ indicates that an increase in *z* affect profits positively, while a negative $SV_{\pi z}$ value indicates that an increase in *z* reduces profits. The impact of *z* can also be expressed by the elasticities $\varepsilon_{\pi r} = \partial\ln\pi^V/\partial\ln z$. If $\varepsilon_{\pi z} > 0$ an increase in *z* leads to increased profit.

We estimate the effects of sea lice prevalence on firm profits by estimating a translog profit functional form (e.g. Atkinson & Halvorsen, 1976; Asche, Roll and Tveterås, 2016). The translog profit function is specified as:

$$\ln\pi = \beta_0 + \Sigma_i\beta_i\ln p_i + 0.5\Sigma_i\Sigma_j\beta_{ij}\ln p_i\ln p_j + \Sigma_k\beta_k\ln z_k + 0.5\Sigma_k\Sigma_l\beta_{kl}\ln z_k\ln z_l + \Sigma_i\Sigma_k\beta_{ik}\ln p_i\ln z_k$$

$$+ \Sigma_k\beta_t D_t + \Sigma_t\Sigma_i\beta_{ti}D_t\ln p_i + \Sigma_t\Sigma_k\beta_{tk}D_t\ln z_k,$$

where subscripts i and j indicate product and factor prices p, subscripts k and l refer to external factors (i.e. sea lice prevalence) and subscript t refers to time. The cost share equations and one revenue equation, obtained by Hotelling's Lemma, are $S_i = \partial\ln\pi/\partial\ln p_i = \beta_i + \Sigma_j\beta_{ij}\ln p_j + \Sigma_k\beta_{ik}\ln z_k + \Sigma_t\beta_{ti}D_t$,

which are negative for inputs and positive for output. To improve the efficiency of the parameter estimates, all the parameters β of the above profit function (1) are estimated together with the share equations S_i in (2) using Zellner's SURE. Symmetry and homogeneity of degree one in factor prices are also imposed on the parameters. Profit models are estimated both with pooled intercept β_0 and firm-specific intercepts to account for firm heterogeneity.

From the estimated system of profit and share equation, we can derive the profit elasticity with respect to the external effect, which is defined as the partial derivative of the log of the profit function with respect to the log of the external effect (i.e. sea lice prevalence), given by: $\varepsilon_k = \partial\ln\pi/\partial\ln z_k = \beta_k + \Sigma_l\beta_{kl}\ln z_l + \Sigma_i\beta_{ik}\ln p_i + \Sigma_t\beta_{tk}D_t$. If $\varepsilon_k > 0$ profits increase with the external effect.

6.2.2. Cost function specification

In order to disentangle different effects on production costs we undertake an econometric analysis of production costs. We estimate a cost function which enable us to separate the effects of input prices, scale economies, technical change and external effects on production costs in salmon farming. The translog cost function is specified as (Berndt & Christensen, 1973; Binswanger, 1974; Tveterås, 2002):

$$\ln C = \alpha_0 + \Sigma_i\alpha_i\ln w_i + 0.5\Sigma_i\Sigma_j\alpha_{ij}\ln w_i\ln w_j + \alpha_y\ln y + 0.5\alpha_{yy}(\ln y)^2$$

$$+ \Sigma_i\alpha_{iy}\ln w_i\ln y + \Sigma_t\alpha_t D_t + \Sigma_t\Sigma_i\alpha_{it}\ln w_i\cdot D_t + \Sigma_t\alpha_{yt}\ln y\cdot D_t$$

$$+ \Sigma_k\alpha_k\ln z_k + 0.5\Sigma_k\Sigma_l\alpha_{kl}\ln z_k\ln z_l + \Sigma_i\alpha_{ik}\ln w_i\ln z_k + \Sigma_t\Sigma_k\alpha_{kt}\ln z_k\cdot D_t + u.$$

In this model C is inflation-adjusted cost of production, y is output level, w_i is the inflation-adjusted price of input i (i = Feed, Labor, Capital), z_k is an external effects (firm average mean adult female sea lice per salmon), D_t is a vector of time (year) dummy variables (t = 2012, …, 2018) for the years after the base year 2012, u is a stochastic error term, and α are parameters to be estimated. The model can account for firm heterogeneity by substituting the pooled intercept α_0 with firm-specific intercepts, which is done in some model specifications estimated here. To improve the efficiency of the parameter estimates, the cost function is estimated together with the cost share equations $S_i = \partial \ln C/\partial \ln w_i$, using Zellner's seemingly unrelated regression technique (Zellner, 1962).

The above econometric model specification allow us to decompose technological progress (TC) into four components: (1) neutral ($TC_N = \Sigma_t \alpha_t D_t$), (2) input biased ($TC_I = \Sigma_t \Sigma_i \alpha_{it} \ln w_i \cdot D_t$), (3) scale biased ($TC_Y = \Sigma_t \alpha_{yt} \ln y \cdot D_t$) and (4) external effect biased ($TC_Z = \Sigma_t \Sigma_k \alpha_{kt} \ln z_k \cdot D_t$) components. The rate of technical change (TC) with these four components is specified as $TC = TC_N + TC_I + TC_Y + TC_Z = (\alpha_t - \alpha_{t-1}) + \Sigma_i((\alpha_{it}\cdot - \alpha_{it-1})\ln w_i) + ((\alpha_{yt}\cdot - \alpha_{yt-1})\ln y) + \Sigma_k(\alpha_{kt} - \alpha_{kt-1})\ln z_k$. If there is technical "progress" this cost based measure is negative. The rate of technical change is our measure of how innovations and other factors influence productivity growth. It is not possible to obtain a "pure" measure of the effects of innovations as it is hard to identify variables that measure innovations and the adoption of these. Moreover, in a biological production sector such as salmon farming the TC measure will also be influenced by biophysical shocks such as diseases. It is therefore possible to obtain negative rates of technical change.

The cost function also allow us to derive the elasticity of costs with respect to the level of the external effect, defined as $E_z = \ln C/\partial \ln z_k = \alpha_k + 0.5\Sigma_l \alpha_{kl} \ln z_l + \Sigma_i \alpha_{ik} \ln w_i + \Sigma_t \alpha_{kt} D_t$. If E_z is positive (negative) then costs increase (decline) with increasing levels of the external effect (ie. sea lice prevalence).

6.2.3. Empirical results from cost and profit function

We estimate translog cost and profit functions on an unbalanced panel data set of salmon aquaculture firms, both models with pooled and firm-specific (firm dummy) effects. For the cost functions we have two definitions of the dependent cost variable, one definition including only the inputs we have prices on (i.e. feed, labor, capital), and one cost variable definition including all cost items. The latter cost variable can capture effects of sea lice on all cost items, but with potential biases due to missing input prices.

Table 6.1 presents sample mean elasticity estimates from the estimated translog cost and profit function on the effect of sea lice prevalence. The full set of parameter estimates can be obtained from the authors. The results are mixed. Overall, an increase in sea lice prevalence is associated with an increase in production costs. However, the effect is only statistically significant when full production costs is the dependent variable. For profits the effect of an increase in sea lice prevalence is significantly negative when we estimate a pooled model, i.e. lower sea lice prevalence is associated with higher profits, but not significantly different from zero when we include firm-specific effects in the profit function.

Table 6.1. Estimated mean elasticity with respect to average adult female sea lice per salmon from translog cost and profit functions

Model	Estimate	Std.error	t-value	p-value
Pooled cost	0.019	0.013	1.53	0.127
Firm effects cost	0.015	0.012	1.20	0.229
Pooled full cost	0.044	0.016	2.72	0.006
Firm effect full cost	0.030	0.017	1.73	0.084
Pooled profit	-0.152	0.072	-2.12	0.034
Firm effect profit	0.027	0.030	0.92	0.358

*No. of observations is 513 for cost functions and 506 for profit functions.

We also examine the pattern of change in cost productivity over time as measured by the rate of technical change (TC). All estimated cost functions predict technical regress on average during the 2012-2018 time period, ie. an upwards shift in costs, ranging from 2.9% to 6.9% across models, as shown in table 6.2. Although technology in reality should improve over time due to new innovations, our finding may be due to a combination of new government regulations being introduced, for example related to sea lice, and biophysical shocks. The component of technical change related to sea lice prevalence (TC_Z) had very limited contribution to technical change, accoring to our estimates. We do not identify any structural breaks from 2017, when the TLS was introduced, according to the model estimates. The rate of technical change continues to contribute to increasing costs. Hence, the slight reduction in production costs we observed in figure 3.5 may have been due to e.g. lower input prices.

Table 6.2. Estimated annual rate of technical change (TC) and its external sea lice effect component (TC_Z) from translog cost functions

Year		2013	2014	2015	2016	2017	2018	Mean
Pooled cost	TC_Z	0.007	-0.018	-0.153	0.211	-0.032	-0.058	-0.007
	TC	0.046	0.024	0.000	0.048	0.026	0.031	0.029
Firm effects cost	TC_Z	0.112	-0.062	-0.084	0.139	-0.065	-0.037	0.000
	TC	0.057	0.037	0.027	0.049	0.043	0.025	0.040
Pooled full cost	TC_Z	-0.041	0.002	-0.069	0.084	-0.034	0.016	-0.008
	TC	0.092	0.001	0.078	0.058	0.076	0.047	0.059
Firm effect full cost	TC_Z	0.057	-0.066	-0.040	0.014	-0.031	0.056	-0.003
	TC	0.109	0.018	0.089	0.053	0.099	0.048	0.069

7. Future policies and regulation of aquaculture production

In this chapter we discuss future policies and regulation of aquaculture production. Factors influencing policies and regulation are sustainability considerations, environmental and biological externalities, economic efficiency, international competitiveness, new knowledge and innovations. Salmon aquaculture is a dynamic industry, experiencing technological, social and economic changes from production to markets. This means that today's regulation may not be appropriate or economic efficient tomorrow.

7.1. Considerations in future regulation of aquaculture

Based on policy objectives and economic efficiency considerations the following should be taken into account when designing future policies and regulation of aquaculture production:

- Regulations should be based on *research knowledge and documentation*: Policy and regulations should utilize the best available knowledge, preferably transparent research based knowledge.

- Regulations should contribute to *efficient use of oceans and other aquatic environments*: Coastal areas, rivers and lakes have value for both production and recreational activities. Regulations should recognize that different geographic areas have different economic value for different production and recreational activities, and these economic benefits should be assessed or estimated. In some coastal areas the societal economic value of aquaculture is high relative to other production and recreational activities, and this should be accounted for in regulation.

- Regulations should ensure that *animal welfare standards* are met: The knowledge and concern for fish welfare has increased over time, and policies and regulations should ensure acceptable level of fish welfare.

- Regulations should contribute to the *international competitiveness* of the aquaculture sector: Norwegian salmon aquaculture competes internationally with salmon produced in other countries, and with proteins from other fish and terrestrial animals, implying that the effects of regulations on e.g. cost competitiveness needs to be considered. Salmon aquaculture should be able to compete on equal terms with other private sectors for labor and capital.

- Regulations should provide appropriate *incentives for economic efficient firm decisions* on investments and allocation of inputs in aquaculture production in the short and long run: Salmon aquaculture firms make decisions involving large and risky investments in fixed capital and biomass capital. Policies and regulations should not impose unnecessary economic risks on investments, and incentivize firms to make decisions that lead to appropriate mitigation of external effects and efficient use of scarce capital, labor and other resources.

- Regulations should contribute to *consistent sustainability standards across terrestrial and aquaculture food producing sectors* in terms of environmental and climate effects, food safety, nutritional concerns, productive efficiency and animal welfare: A kilo of meat produced from aquaculture and agriculture should be subject to the same standards for assessing and balancing economic, social and environmental considerations, cf. UN's sustainable development goals. Different standards can lead to societal economic inefficiency losses. External environmental effects should be treated similar across sectors of the economy, and in particular across terrestrial and aquatic food production sectors. For example, a tonne of Co2 emitted to the atmosphere has the same effect on climate whether it originates from agriculture or aquaculture.

- Regulations should *limit societal costs of ensuring regulation compliance* in terms of costs in public and private sector: This include designing appropriate systems involving both public and private sector for processing applications and monitoring compliance, finding appropriate balances between public regulation and corporate internal control systems with third party certification, and ensuring equal treatment of aquaculture producers across regions and other dimensions.

- Regulations should provide *incentives to innovations that account for both internal and external costs* of aquaculture production: This includes technologies which are closed or semi-closed and thus have smaller or no external disease pressure and environmental emissions. It also includes technologies that allows for production in sea areas which may contribute less to external costs, such as offshore sea areas. It also includes innovations that reduce disease pressure and emissions from existing inshore open cage farms.

- Regulations should have mechanisms that *provide revenue to central and local government to fund public services*: This include pricing of new licenses (through auctioning or other mechanisms) and government taxes or fees on producing firms (e.g. profits, production, environmental emissions). The tax structure and tax levels must be designed to take into account the other considerations presented here (e.g. international competitiveness, incentives to innovate).

7.2. New knowledge and innovation

We can expect innovations in many areas towards 2030 – biological, technological and organizational innovations. Innovations will partly be a response to challenges and opportunities the aquaculture sector experience today. But new and unexpected biological, environmental and market challenges and opportunities will also emerge, adding to the need to innovate. Much of this innovation will be based on new research based knowledge.

New research based knowledge and innovations will create new structural conditions for government policies and regulation in 2030. In particular, innovations can be expected to change

(1) Environmental and biological external effects from aquaculture farms, and consequently costs imposed on other farms and other sectors and stakeholders.
(2) Choice of regulations based on technical opportunities for measurement of emissions and effects on the environment and other stakeholders.
(3) Costs of different regulations aimed at limiting external effects.

Potential sources of negative external effects are the following different types of "emissions": (1) Diseases, (2) sea lice, (3) organic emissions, (4) salmon escapees. Today, government indirectly limits emissions from farm locations through a combination of constraints on the maximum allowable biomass (MAB), constraints on the density of fish in the cages and the number of fish in each cage, constraints on sea lice per individual salmon, sanitary requirements and standards on production and transportation activities, and technical standards.

Present regulation of aquaculture, using MAB regulation for firms, farm sites and production areas, is not the most direct if the aim is to mitigate emissions and disease pressure from production activities. Regulation of emission levels would be much more direct. The current use of MAB is partly due to the fact that current measurement technologies do not allow government to measure emission and disease pressure levels with a sufficient precision and at sufficient low costs. In the future innovations can increase measurement precision and reduce costs for:

- Emissions and effects on benthic fauna on farm sites and beyond.
- Population of parasites (sea lice), dispersion and effects of these, and the contribution from individual farm sites to parasite population dynamics.
- Disease pressures, effects of diseases and contribution from individual farm sites.

Towards 2030 and beyond we should expect to increase our knowledge about relationships in the marine ecosystem, including the role of aquaculture production activities. In future regulation av ocean areas epidemiological models (with hydrodynamic and biological sub models) should give much stronger predictive power for ocean areas and farm sites, and thus a much better knowledge foundation for efficient government regulation.

7.3. Regulation of multi-technology aquaculture

The dominant production technology in salmon aquaculture is open cages in sheltered waters. In Norway, the regulatory system reflects this fact, and the focus is primarily on how to best regulate the industry and the environmental challenges it creates based on this system.

In recent years salmon producers has experienced increased sustainability challenges, and public debates related to environmental impacts and sharing of value creation has further contributed to a slowdown in production growth in Norway, the leading salmon producer globally. To overcome these challenges, substantial investments in R&D and innovations have led to the emergence of new salmon production technologies that is outside of the standard regulatory system and which may be expected to reduce the environmental impact. These range from onshore production that have a separate regulatory system via closed or semi-closed production systems in sheltered seawaters to offshore ocean farms. This range of technologies can provide new opportunities for social acceptability and accordingly for the industry to grow in a sustainable manner. However, the new technologies may also have larger environmental footprints than today’s conventional technology in some areas, such as climate emissions. Moreover, these technologies allow for different combinations of technologies in different stages of the value chain from smolt via post-smolt to grow-out salmon production, as shown in figure 7.1.

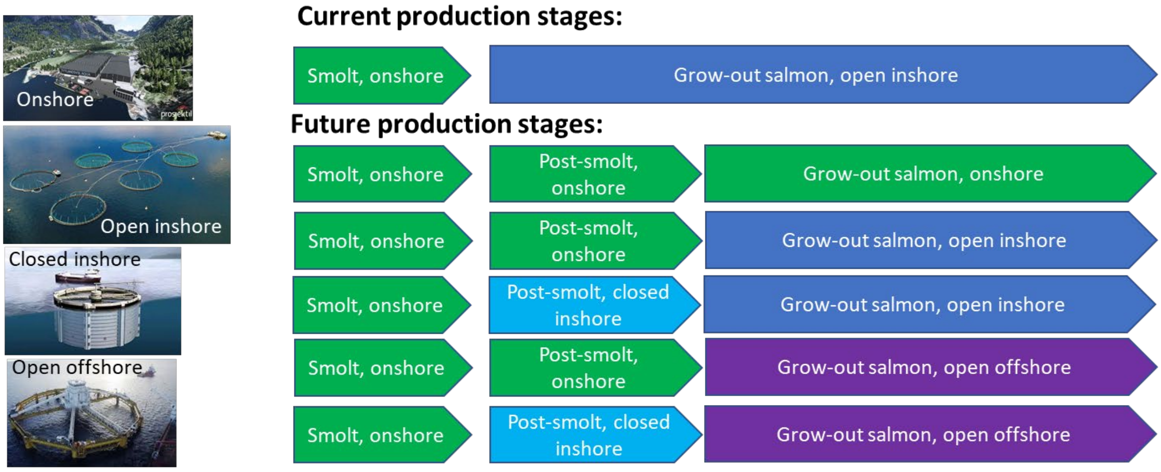

Figure 7.1. Current and future configurations of upstream salmon aquaculture value chains

A central challenge is to design consistent future regulations for various aquaculture production technologies which take into account their differences in environmental impacts, user conflicts, other social impacts and productivity, and balance these considerations appropriately. Different salmon production technologies will probably face a range of co-existence challenges with other user interests, and expectations from local communities of a fair sharing of economic returns.

The internal and external economies of different productions systems will not be identical. Investment costs, financial risk, production costs and external costs per kilo of salmon produce can be expected to differ across production systems such as open cage inshore farms, closed inshore farms and offshore farms. A central challenge for governments is to provide incentives for aquaculture firms to make investments that internalize not only their internal productivity, but also the external environmental and social costs and benefits of different technologies. Ideally, regulations should align society’s concerns with aquaculture firms’ investment decisions.

A consensus has emerged in the Norwegian society that salmon aquaculture, in addition to paying ordinary taxes, should provide extraordinary revenue to central and local government to fund public services, currently through selling of new production capacity and a production fee per kilo of salmon produced. The fiscal design can together with other quantitative regulations have significant effects on innovation and investment in different technologies with different external effects. Today, high prices are paid for new maximum allowable biomass (MAB) in conventional inshore open cage farming. But it took many years of innovation before conventional salmon farming achieved financial returns that provided incentives to aquaculture decision makers to undertake high upfront payments for additional production capacity. New technologies such as closed-/semi-closed farms and offshore farms will probably not be able to pay the same high fees for new MAB at the early stages as conventional farming.

The high fees that are currently paid may also reflect that limited new capacity is made available by government. This is a consequence of assessments on the sustainability of growth made in the traffic light system, in particular with respect to sea lice induced mortality rates for wild salmon. However, closed-/semi-closed farms and offshore farms are expected to have small or no effect on wild salmon through sea lice. If sustainable growth of aquaculture value added and employment is an objective for society, then a regulatory mechanism is to introduce separate production license classes for closed-/semi-closed farms and offshore farms with pricing of production capacity that provide sufficient incentives for investment to capital providers.

Table 7.1 suggests a possible differentiation of production regulation with separate types of production licenses for onshore farms, open cage inshore farms, closed or semi-closed farms and offshore farms. In principle, these different production licenses could have separate pricing for new production capacity, for example, separate auctions. In some production areas it may not be sustainable to expand production because of high negative environmental externalities, e.g. when the production area has a red light in the traffic light system. On the other hand, increase in production using closed or semi-closed technology can be sustainable. But then society's pricing of production capacity must provide incentives allow for reasonable financial rates of return on private investment in these technologies. This can be made possible by separate auctioning or appropriate fixed prices for closed or semi-closed production licenses.

Table 7.1. Production technologies and government license to produce and innovate

Production technology	Commercial full scale production
Onshore	«Free» entry limited by emission licenses, access to water, energy etc.
Open cages inshore	MAB and traffic light system, priced by society for new capacity (existing)
Closed/semi-closed cages inshore	Specific license with emission/technical standards/requirements, regulation of production capacity (MAB) and pricing (new)
Offshore	Specific license with regulation of production capacity (MAB) and pricing (new)

The expansion of aquaculture production to offshore ocean is not trivial. As suggested by table 7.2 the regulation inshore and offshore will involve different public authorities. In addition, different concerns on biosecurity, environmental impacts, human safety and other issues in inshore and offshore aquaculture means that regulation has to be designed differently in various areas.

Table 7.2. Regulation of inshore and offshore aquaculture

Type of regulation	Inshore (current)	Offshore (future)?
Production capacity	Max. allowable biomass (MAB)	Max. allowable biomass (MAB)?
Farm location/area	Municipality and county	Directorate of fisheries
Health/work environment/safety	Labour inspection Authority	Maritime Authority
Production equipment&structures	Directorate of Fisheries	Directorate of Fisheries / Maritime Authority
Biology	Food Safety Authority	Food Safety Authority
Marine Environment	County Governor	Environment Agency

7.4. Concluding comments

The central premise for regulating aquaculture from the Norwegian parliament ("Stortinget") is that society should contribute to the greatest possible value creation and facilitate predictable and environmentally sustainable growth. Current regulations of production and growth use the maximum permitted biomass (MAB, or "MTB" in Norwegian) of live fish that the farmers can use in the cages as a key mechanism for limiting production. MAB limits production at farm sites, in larger production areas and nationally. At farm sites, MAB production limitation is set according to measurements and assessments of capacity for organic emissions, and measurements of sea lice attached to farmed salmon. For larger production areas, production is regulated over time on the basis of society's assessments of the pressure salmon lice have on stocks of wild salmonids. The assessments of sea lice induced pressure leads to a traffic light for production areas in relation to further growth. For a company, the opportunity to buy MAB growth depends partly on the prevalence of sea lice at its own fish farms, and partly on the traffic light to the production areas where the company produces.

The regulation of growth in production has over time made significant progress, both in terms of the knowledge base and the mechanisms used in the regulations. Society today has access to far greater knowledge about biology, biosecurity and environmental impacts than in the industry's childhood. This knowledge has also helped to introduce regulatory mechanisms that can more appropriately take into account both value creation and environmental impacts of salmon farming. At the same time, the large growth in production from the 1990s until today in localities and in larger sea areas has also created new challenges for biosafety and the environment, which require society to consider changes in regulations.

Looking towards 2030, current regulations may not satisfy the Norwegian parliament's expectations for growth in value creation, predictable and environmentally sustainable growth. There are several challenges with current regulations, both the design and the practice of these:

- The scientific knowledge base for the regulations is too weak in several areas. This applies, for example, to connections between aquaculture production, salmon lice populations and effects on stocks of wild salmonids.

- The requirements for documentation and the actual documentation of connections and status for influencing recipients are often too weak as a basis for decision-making for the administration.

- Public agencies are to varying degrees able to apply state-of-the-art research-based knowledge.

- There are different practices of regulations along the coast, partly based on different knowledge in different public agencies.

- The mechanisms for growth and reduction in production do not sufficiently reward companies that, through investments in innovations and better operations, reduce their impact on the environment.

- MAB is used as a regulatory mechanism to limit several types of impact simultaneously. For some types of impact, an indirect regulation such as MAB is imprecise and ineffective. If society, on the basis of a scientific knowledge base, finds that farm sites or larger sea areas are to be regulated in order to limit a type of impact, a more direct regulation of the impact can be more effective.

- The traffic light system has some generally valid premises in principle, but the practical implementation of the traffic light system may have significant weaknesses related to its knowledge base and design of mechanisms.

In sum, the current regulation should be further developed towards 2030 from restricting production to restricting environmental impacts, designing regulatory mechanisms that align aquaculture producer incentives with society’s sustainability concerns, and with stronger requirements for a documented knowledge base as made possible by new research results and digital innovations.

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