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Cost development in Atlantic salmon and rainbow trout farming:

What is the cost of biological risk?

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Report 41-2022, NORCE Health and Society

Report title	Cost development in Atlantic salmon and rainbow trout farming: What is the cost of biological risk?
Project number	NFR 320612
Institution	NORCE Health and Society
Principal	Norwegian Research Council / Research Council of Norway
Gradient	Open
Report No.	41-2022, H&S
ISBN	978-82-8408-263-9
Number of pages	73
Publication date	November 2022
CC License	CC BY 4.0
Index entry	Costs, biological risk, aquaculture, aquaculture, salmon, rainbow trout, salmon lice, fish diseases and fish feed

Summary

Since the commercial breakthrough in the early 1970s, salmon farming in the sea has gone from being a small-scale industry to one of Norway's largest export industries. Although Atlantic salmon and rainbow trout farming represents only a few percent of the world's aquaculture production, the Norwegian aquaculture industry is a leader in many areas. Initially, production technology was simple and small-scale, but with increased experience, knowledge, and constant innovations in construction technology, nutrition and fish health, productivity in the aquaculture industry increased dramatically. The twenty-year period between the mid-1980s and the mid-2000s was characterised by high productivity growth, which resulted in a substantial reduction in costs, which in turn led to lower salmon and trout prices (Figure 1). [1],[2,3]

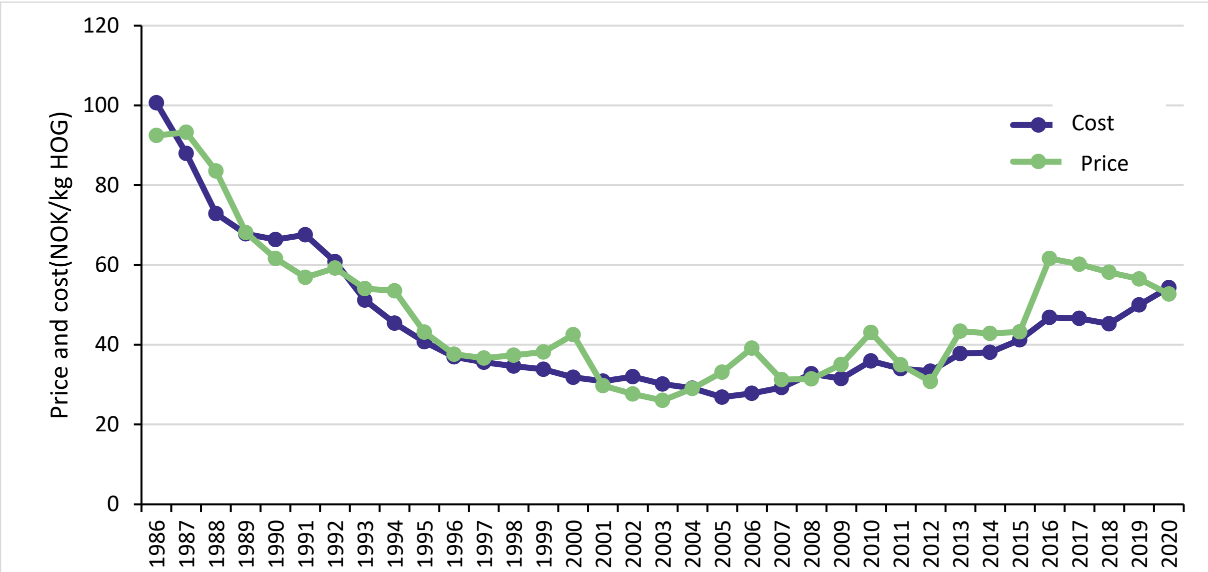

Figure 1. Price and costs 1986–2020 in NOK per kilo gutted weight. Sources: Directorate of Fisheries 1986–2020. Capital costs are separate calculations.

Production grew by almost 20 percent annually between 1980 and 2005. The cost decline reversed around 2005, and between 2005 and 2020 production costs increased by 176 per cent in nominal terms (102 per cent in real NOK). The cost increase has averaged 7 percent per year, several times faster than inflation. [4]

The cost increase has continued even after 2020 and is approaching NOK 60/kg gutted weight including capital costs. Despite the fact that salmon prices have remained at a relatively high level since 2016, the cost increase has caused profitability to fall. In 2020, the operating margin was lower

[1] The 1970s were the breakthrough in the sea. There was already a production of trout on land in the 50s and 60s., see e.g. Berge (2002).
[2] See Reve and Sasson (2012) and Tveterås et al. (2019).
[3] See Afewerki et al. (2022).
[4] Including capital costs. The costs reported in the Directorate of Fisheries' profitability surveys have increased by 148 and 82 per cent in nominal and fixed NOK respectively.

than it was in 2005. The development should worry more than just salmon farmers. Risk in the industry increases with rising costs. A steadily higher salmon price will be necessary to cover a normal return. [5]

The purpose of this report is to investigate the reasons behind the cost explosion, with a particular focus on biological risk. Nofima and Kontali have previously carried out several thorough analyses of factors such as lice, smolt and capital. [6] "Biological costs" is a cost item that is widely discussed, but little studied. The focus of this report is therefore to assess the cost of biological risk factors such as lice and disease. This is a topic that is becoming increasingly important, and in the academic literature it is referred to as the Global Burden of Animal Diseases (GBADs). [7] The effects of biological risk in aquaculture are also an example of the tragedy of the *commons (Tragedy of the Commons*), where diseases and lice spread from one facility to another, so that the decisions made by one farmer will also affect the other fish farmers in the vicinity in a negative way and contribute to cost increases for the entire industry.[8]

In summary, the most important cost drivers since 2005 are:

1. **Higher prices for factor inputs.** The price of important input factors has risen, especially for feed. The feed price increased by ~50 per cent between 2005–2020 measured in Norwegian kroner (2020-NOK). Since the price formation of several of the input factors in fish feed takes place in a global market (listed in USD), the depreciation of the krone has contributed to higher feed prices. Since 2020, the krone, particularly against the USD, has depreciated further, and prices for important input factors have risen (partly as a result of the Ukraine crisis) will put further pressure on production costs ahead.

2. **Increased capital intensity.** Investment growth in fixed assets, hatcheries, operating and special boats, processing plants, etc. has resulted in increased capital costs, both in the form of larger depreciation and higher capital return requirements. Investment growth has been driven by a need to be able to produce more fish (e.g. larger hatcheries), a need for larger vessels, but also as a result of stricter regulations (see point 4 below).[9]

3. **Biological risk.** All industrial production of food will involve biological risk (disease, stress, reduced growth and mortality). In salmon farming, disease and lice in particular represent the greatest sources of biological risk, but the effects can also be amplified by suboptimal plant operations and treatments (e.g. specific delousing methods). The costs of biological risk have increased considerably over the past decade, and coincide with a number of changes and incidents in the aquaculture industry in the same period, which makes it

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[5] By normal return is meant the profitability necessary for to cover all costs, including return on invested capital. In other words, the sum of operating and capital costs.
[6] See e.g. Iversen et al. (2019).
[7] See e.g. https://pubmed.ncbi.nlm.nih.gov/34542092/
[8] See Estay and Stranlund (2022).
[9] See Blomgren et al. (2019a; 2019b) and Misund et al. (2019a, 2019c) for more on investments in aquaculture.

difficult to point to a single main cause. Stricter lice limits were introduced in the period 2008–2013, and may have contributed to increased delousing intensity after 2012. Around 2015, the effectiveness of chemical delousing agents dropped dramatically, leading to a sharp increase in relatively unproven new non-medicinal delousing technology (mechanical and thermal). Parts of the country were also affected by increased incidence of viral diseases such as PD, ISA, and CMS (heart rupture). There has been increased mortality from large fish in connection with non-medicinal delousing, and heart ruptures are often detected. Since 2010, the average weight of dead fish has increased from about 1 to more than 2 kilograms. When the price of input factors increases, so does the cost of the dead fish. Increased dead fish weight will amplify the effect on production costs of increased input prices. The combination is an important driver of the increased costs seen over the past 10 years. Furthermore, biological problems can lead to forced slaughter and lower slaughter weights, which both increase costs and reduce achieved price (due to price discounts for smaller fish). Diseases and parasitic infections that affect the appearance of fish can result in lower quality grading and thus price discounts. Biological problems will also result in suboptimal utilisation of production capacity, so that fixed costs are distributed across fewer kilograms. Smolt quality may also be a potential explanatory factor, and this has been much discussed recently.

4. **Regulations.** Regulations affect costs and profitability through various mechanisms. In isolation, stricter lice regulations will increase fish farmers' costs, and costs for some companies will increase more than others as a result of differences in lice pressure. Environmental regulations (lice, disease, escapes, emissions) mean that production growth cannot keep up with demand growth, and provide extraordinary profitability, in the form of a *regulatory rent (policy rent)*, which in turn motivates activities that can increase costs (see next point). The combination of stricter lice regulations and fish farmers' response to more frequent and intense delousing may have contributed to the development of salmon lice resistance to chemical agents in the period up to 2015/2016. A subsequent rapid growth in non-medicinal lice treatment has resulted in increased mortality of large fish. Furthermore, fish farmers with biomass close to the MAB[10] limits will have incentives to invest in increased MAB utilisation. MAB limits that only bind for a short period in the autumn will motivate increased MTB utilisation in the rest of the year if it is profitable (the mechanism is explained in point 5). The same applies to incentives for increased utilisation of a company's total MAB (group, company and site MAB). For example, a reduction in the production cycle (e.g. with large smolt) could increase MAB utilisation.

5. **High price**. Increasingly stringent environmental and fish health regulations in both Norway and other production countries have resulted in high global market prices for farmed salmon and rainbow trout. The purpose of the regulations is to reduce the industry's environmental impact from lice, escapes, disease, etc. Examples of environmental and fish health regulations in aquaculture are the traffic light system (salmon lice), the lice regulations (salmon lice), technology requirements (escapees), and

[10] Maximal allowable biomass (MAB) are limits for how much biomass the farmers are allowed to have in their farms at any given time.

distance requirements between locations (biosecurity). Not least, national and regional authorities have been reluctant to increase production capacities and approve new sites, which in itself has been an important production-limiting measure. The result has been that production growth over the past decade has been low compared to previous periods, and has resulted in higher salmon prices and profitability. At the same time, with current regulations, there are still opportunities to grow production both along the intensive (e.g. increased utilization of MAB capacity) and the extensive margin (e.g. purchase of new MAB capacity, development permits and other non-commercial permits). As long as the marginal income from increasing capacity utilisation exceeds its marginal cost, it will be economically profitable to do so. Strategies aimed at increasing capacity utilisation, e.g. post-smolt strategies, may therefore be drivers of higher costs and capital intensity. [11]

"Biological costs" are not reported directly, either by companies or by the Directorate of Fisheries, and must therefore be estimated on the basis of other sources of information and be based on certain assumptions that could potentially give rise to measurement errors. The complexity of the relationships between lice infestations, lice treatments, and diseases, etc. complicates the isolation of the costs of lice from other biological problems. Direct costs of lice treatments can be calculated, but what about the indirect costs caused by stress, reduced growth and increased susceptibility to diseases? Some diseases such as CMS, in combination with mechanical and thermal lice treatments, can lead to mortality. What, then, is the source of mortality, is it the lice infestation, the viral disease, or the combination?

There are individual estimates of the cost of lice and diseases, but so far no aggregate level estimates. This report therefore uses a more general measure of biological costs. It is based on the economic feed conversion rate. The feed conversion rate will be influenced by many elements of production, e.g. feed waste, cleaner fish eating feed, changes in feed composition, but mainly factors such as disease, stress, starvation and death will be the main causes of high feed conversion rate. The discrepancy between an economic and an optimal biological feed conversion rate is therefore an indirect measure of biological risk.

The discrepancy between the realized economic feed conversion rate and theoretical feed conversion rates (ideal / utopian) of 0.9 and 1.0 respectively is used to estimate the indirect biological costs. The direct biological cost is estimated as a proportion of the "other" operating cost, and the total biological cost is calculated as the sum of the indirect and direct costs. Two estimates are presented, one of which (an ideal feed conversion rate of 0.9) should be regarded as an upper estimate of the private costs associated with biological risk. The second estimate (an ideal feed conversion rate of 1.0) will indicate costs where factors such as feed waste etc. will also be included.[12][13]

[11] With *intensive* is meant that existing capacity is better utilised, whereas with *extensive* is meant increased capacity (e.g. more sites, more MAB).

[12] Part of the other operating costs are allocated to the biology cost based on a key of 25 % calculated from historical analyses of other operating expenses 2015–2020.

[13] Private costs are used for corporate costs, while social costs are used for society's costs.

The method is simple, which has its advantages and disadvantages. The disadvantages are that the method is based on some simplifying assumptions, which give measurement errors and imprecise estimates. Biological cost estimates are sensitive to the reference level of the ideal feed conversion rate. The advantage of the method is that one can use publicly available data to estimate the level of the "biological" costs. One of the most important contributions to the report is to demonstrate that it is useful to calculate the costs of biological risk, since they can be significant. Development over time, and across production areas, is perhaps more useful than the level itself. The analyses of the geographical differences show that production costs across geographies become more homogeneous when adjusted for biological costs. The results also show that more research is needed on this topic. However, more advanced methods that can reduce measurement errors and provide more precise estimates should be developed.

Figure 2 shows the development biological costs since 1994. Costs fell until the mid-2000s, but have been on a rising trend for the following 15 years. The same development has occurred in all production counties (Figure 3).

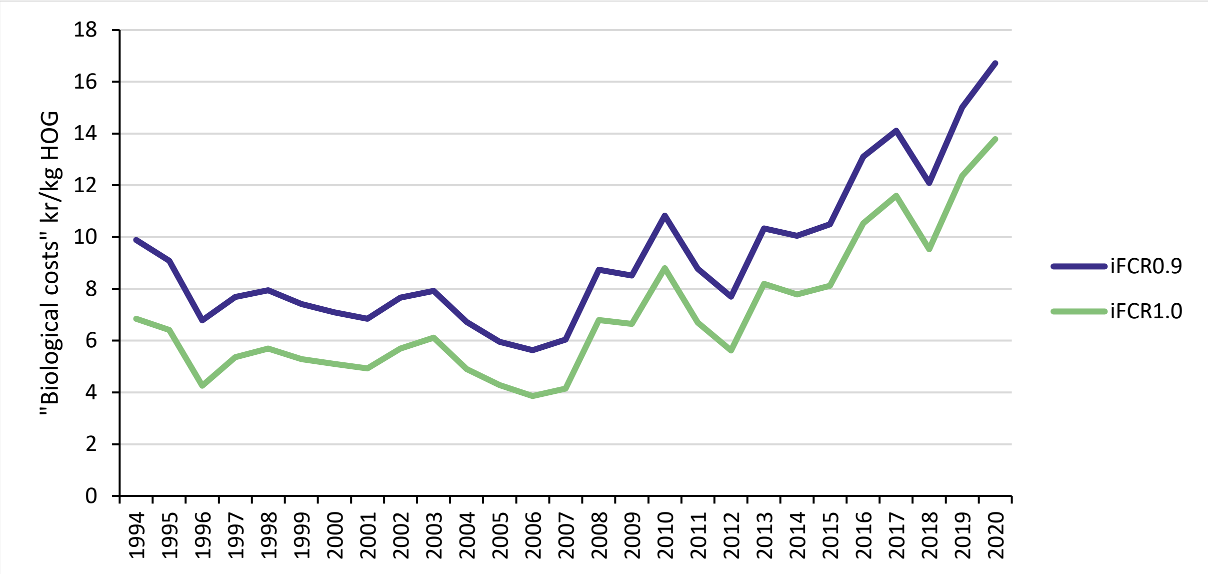

Figure 2. "Biological" costs in fixed 2020 kroner per kilo gutted weight (Head on gutted weight, HOG). Calculated from ideal feed conversion rates of 0.9 (iFCR0.9) and 1.0 (iFCR1.0). Own calculations based on the Directorate of Fisheries' profitability survey.

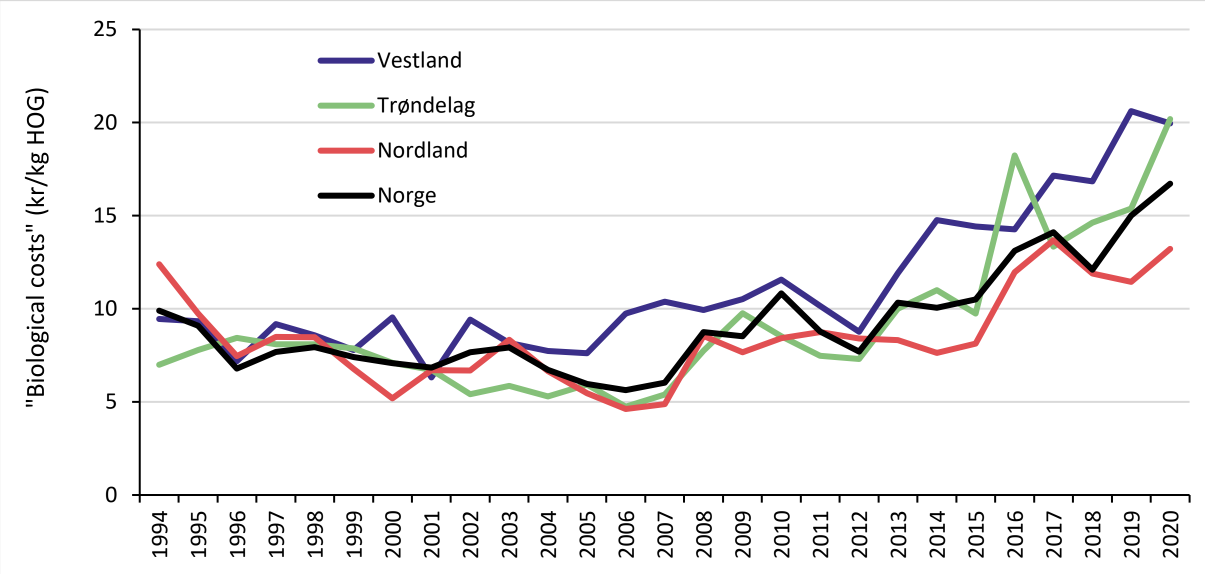

Figure 3. Regional differences in "biological costs" (based on iFCR0.9). Fixed 2020-NOK per kilo HOG. Own calculations based on the Directorate of Fisheries' profitability survey.

Before 2005, regional differences in biological costs were small, while after 2005 the differences have increased. Vestland county has typically had the highest biology costs and Nordland the lowest. Extracting biology costs gives a better picture of the development of the other cost elements. The results show that the variation in feed costs and other costs between fish farmers in different counties is falling dramatically, and document that variation in biological risk is one of the largest contributors to regional differences in production costs.

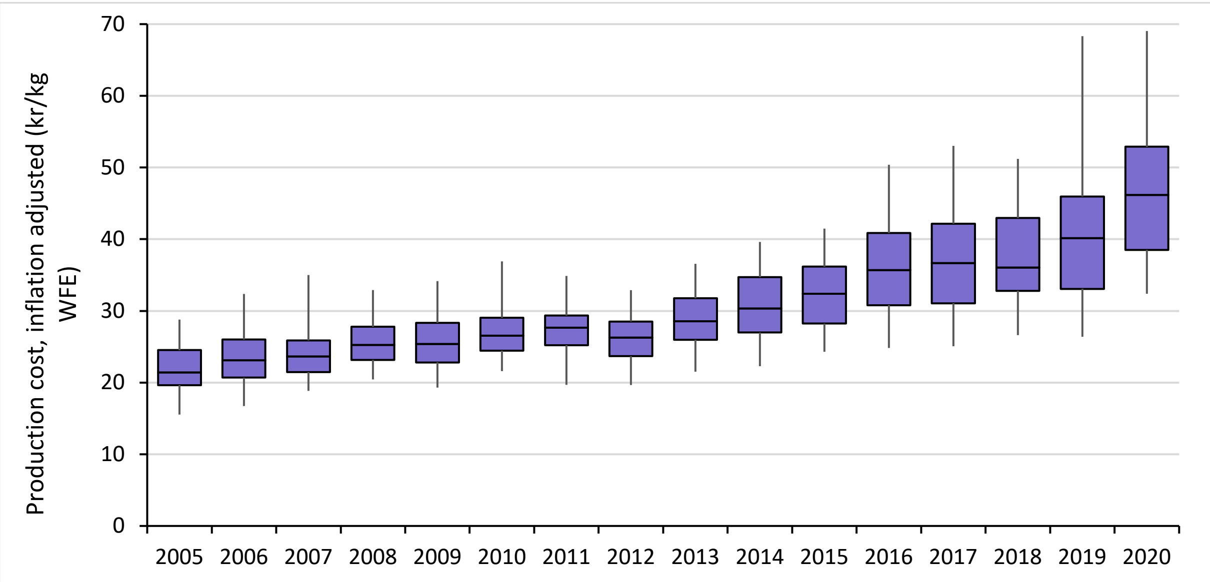

Figure 4. Variation in production costs (NOK/gutted weight). Boxes contain 50% of businesses, while vertical lines contain 90%. The horizontal line in the boxes represents the median. The figures are taken from the Directorate of Fisheries' profitability surveys.

Today, biology costs are one of the largest cost items in salmon farming, and since 2012 they have more than doubled. In addition to a substantial increase in the cost level, there has also been a substantial increase in the *spread* in production costs (Figure 2). Increased cost differences are particularly visible after 2012 and coincide in time with increased biological costs and increases in regional differences in biology costs.

Calculating biological costs is therefore important for several reasons. First, they are not an insignificant cost element in the production of live animals. Without isolation of the biological cost, the other costs will be distributed among the production and overestimate the significance of the other cost elements such as feed, smolt, depreciation, etc. An increased feed cost can mask factors that are actually due to increased biological risk. Furthermore, biology costs will provide veterinary authorities with useful knowledge that can be used to calculate GBADs for aquaculture. For fish farmers, it will be useful information for benchmarking costs between facilities. Not least, isolating biological costs will provide a better picture of the costs of farming in open cages if the purpose is to investigate the profitability of alternative farming technology. A feed cost based on production in open cages with frequent lice infestations will not be relevant to use when calculating the profitability of investments in semi-closed facilities without lice or offshore aquaculture technology. [14]

The analysis also has another important contribution. It shows an increased internalization of negative externalities. Negative externalities is a term economists use to describe costs to society that arise as a result of a company's activities, but which are not borne by the enterprise itself, creating a wedge between corporate and society's costs. Pollution is one such example. The typical textbook example is a factory that pollutes and puts an economic burden on other businesses as a result of the pollution. The classic textbook solution is then to impose an environmental tax (Pigouvian tax) on companies that is set equal to the marginal cost of environmental damage. As a result of the tax, companies' costs will increase with the level of the cost of environmental damage in line with the polluter pays principle. In technical terms, this is called an *internalization* of negative externalities. However, the most important externalities in aquaculture such as lice and diseases are poorly covered by such a classic textbook definition. While the effects of sea lice and diseases from salmon farming on wild salmonids are in line with the classic definition, they do not fully describe the costs to society of salmon lice and fish diseases in aquaculture. The term [15]*spatial externalities* is then more appropriate, describing a situation where businesses pollute each other, and can give rise to the tragedy of the commons. In aquaculture, salmon lice and diseases will spread from plant to facility. This will increase costs for fish farmers in areas with a lot of lice and diseases, and provide a partial internalization of the externalities. Recent research shows that current regulations amplify this effect. The results of the analyses in this report show that society's costs from spatial externalities are significant and are largely borne by the farmers themselves. Stricter environmental and fish health regulations, such as lice limits and the traffic light system, have contributed to an internalisation of society's lice and disease costs. Areas with high lice levels (Vestland) also have the highest biological costs, while areas with low lice levels (Nordland) have the lowest biological costs. These findings will have consequences for the choice of regulations and taxation of the aquaculture

[14] See also Tveterås et al. (2020a; 2020b; 2020c).

[15] See Asche, F., Eggert, H., Oglend, A., Roheim, C. A., & Smith, M. D. (2022). Aquaculture: Externalities and Policy Options. Review of Environmental Economics and Policy, 16(2), 282–305 and Estay, M., & Stranlund, J. K. (2022). Entry, location, and optimal environmental policies. Resource and Energy Economics, 70, 101326.

industry. For example, how effective will an environmental tax on salmon lice on farmed salmon be when fish farmers' lice costs are already high and increase with increased sea lice infection in a geographical area? [16,17] The lice regulations and the traffic light system already provide incentives to reduce lice on farmed salmon.

Furthermore, the results will provide useful information for the optimal design of other taxes, e.g. a resource rent tax. How a resource interest tax will work in an industry where the extraordinary profitability is created by environmental regulations, and the main externalities are partially internalized and of considerable scope, has not been studied academically. By not examining the reasons behind the extraordinary profits in the industry, one can easily be misled to believe the profits are resource rents, not regulation rents (arising from environmental regulation), and propose incorrect policy measures. Nor have the environmental consequences of a resource rent tax in aquaculture been assessed. The fish farmers' direct and indirect costs related to lice, disease and escapes will be deductible in a profit-based [18,19]or cash flow-based resource rent tax. This means that society takes a share of such costs equal to the level of the tax rate (e.g. a subsidy). A marginal tax rate of 78 percent means that society takes a similar share of the biological costs, in other words, the state will cover 78 percent of the biological costs. Other forms of resource rent taxation, such as a royalty, will not have this effect. If society wants to shift investments and activities towards more efficient use of resources, distorting taxes will be more relevant (e.g. environmental taxes, subsidies, etc.). A common criticism of neutral taxes is that they will not provide incentives for more efficient use of resources. That is precisely the purpose of neutral taxes, they should not influence corporate decisions. Taxes on production, MAB or the number of deferred smolt, on the other hand, can all provide possible incentives towards more efficient use of resources, in line with the intentions of a good tax system[20]. At the same time, they will also be a source of tax revenue.

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[16] See Estay, M., & Stranlund, J. K. (2022). Entry, location, and optimal environmental policies. Resource and Energy Economics, 70, 101326.

[17] See Oglend and Soini (2020).

[18] Oglend and Soino (2020) are an exception.

[19] NOU 2019:18 «Taxation of aquaculture» did not assess the environmental consequences of a resource rent tax even if it was part of the mandatebut let on the basis that Current environmental regulations are sufficiente (see page 26–27, section 2.3). Recent research suggests however that environmental regulations reinforce the environmental challenges in aquaculture.

[20] An important ambition for a good tax system is that it "should contribute to, or as little as possible stand in the way of, efficient use of resources" (NOU 2000:18 «Taxation of petroleum activities", p. 28). Taxes that shift towards more efficient use of resources are preferred over neutral taxes.

Thanks

The work in this report was motivated by a question from journalist Bent Are Jensen in Intrafish who wondered what fish diseases cost. There were some studies on lice, but few academic studies on the economic consequences of fish diseases.

This report is funded by the Research Council of Norway project no. 320612 "A unified framework for regulation of multi-technology salmon aquaculture (MULTITECH)" and also benefits from funding from the project "Global Burden of Animal Diseases. GBAD's programme" and the UiS Business School (sabbatical).

The author would like to thank Svein Angell, Edgar Brun, Merete Fauske, Ole Folkedal, Aslak Forus, Bjarne Hatlen, Tord Ludvigsen, Frode Oppedal, Endre Seter, Ragnar Tveterås, Paul Steinar Valle, Cecilie Walde, Håvard Walle, and others for their help and useful information.

About the author

Bård Misund is a professor of Finance at the University of Stavanger Business School. He holds a M.Sc. in aquaculture biology, M.Sc. in Finance and PhD in Industrial Economics. Misund has previously worked in both the energy and seafood industries. He participates in research projects funded both by national and international funding agencies, as well an industry funded research, He also does consultancy work for both industry and public sector.

Content

1. Introduction

The Norwegian Directorate of Fisheries has conducted profitability surveys for fish farming of salmon and trout since 1982. The calculation method for production costs and profitability has changed along the way which may affect comparability over time. For example, from the 2009 figures, business oriented calculation methods were used, against a economics perspective in the period 1982-2008. In the first years of the 1980s, the method changed somewhat, and the Directorate of Fisheries' official time series therefore runs from 1986, not 1982. Different calculation methods can lead to changes in both production costs and profitability.[21]

In addition to average figures for production costs and profitability, the Directorate publishes information on the composition of production costs, achieved salmon and rainbow trout prices for fish farmers, feed prices, feed conversion rate, as well as differences in production costs and profitability for different counties and size groups of companies. Not least, the dataset contains anonymised dispersion tables for production cost, operating margins and feed conversion rate, which provide useful information on variations in these variables. The reasons why the dispersion tables have been included can be read in the Profitability Survey from 1984 (Directorate of Fisheries, 1984, own translation):

> *"One of the things that seems typical for the aquaculture industry, and which has also been demonstrated through all the profitability surveys conducted by the Directorate of Fisheries, is the large variation in operating results. The explanation is naturally the uncertainty that characterises the operation of a fish farm. The plants operate in a natural environment that cannot be controlled one hundred percent. Events in recent years have shown that there is a long way to go before one has full knowledge of this environment. Disease, storms, damage from different organisms are key words that can explain how a good result in an extremely short time can be turned into a negative one. When reading the tables, it should therefore be borne in mind that there is a very large variation in the data."*

The quote above might as well have been written in 2022. Analyses of costs and profitability in aquaculture should therefore also include analyses of the variation of variables across companies and regions, if one is to get a complete impression of developments. This will be discussed later in the report.

The figure below shows developments in average production costs 1974–2020 (Figure 1). Price and cost developments have gone through at least 3 phases. In the first, between 1970 and the mid-1980s, both costs and prices were at a historically high level measured in real kroner. Between the mid-1980s and about 2005, both prices and costs fell. In the last 15 years in the chart, costs have

[21] See eg. Profitability survey for 2009, page 13 for examples of how this can have an impact (Directorate of Fisheries, 2009).

been on an upward trend, and prices have fluctuated around costs. Below, the report will go into more detail on the three phases. [22]

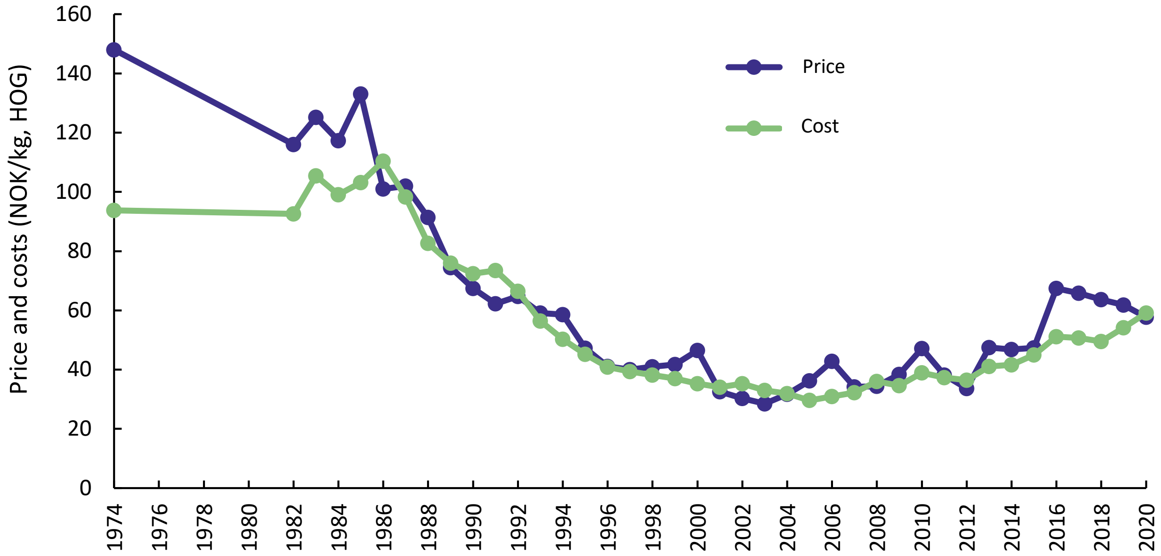

Figure 3. Sales price and production cost 1976-2020 (HOG). The figures are based on the Norwegian Directorate of Fisheries' profitability survey and include slaughter and packing costs. In addition, a cost of capital equal to a required rate of return of 10 per cent multiplied by book total assets has been added. Prices are the achieved price for farmer. All values have been converted to fixed NOK 2022. Sources: The Directorate of Fisheries' profitability survey (1982–2020) and NOU 1977:39 (1974).

Establishment phase 1970–1985

The commercial breakthrough for salmon farming in Norway came in the early 1970s. The octagonal Grøntvedt cages made it possible to produce salmon and trout in the sea. The cages consisted of floating collars made of wood, polystyrene and car tires, and a net. The Grøntvedt brothers' success story spread rapidly along the coast, and the number of farmers increased in number. The technology for farming varied a lot in the beginning. In the beginning, enclosed sea areas were also used. In addition to Grøndvedtmerden, other varieties of flotating cages were also used. The first plastic cage came in 1974, produced by Polarcirkel (today part of AKVA Group ASA). In the 80s, steel construction also became popular. The authorities were unable to decide how large a fish farm should be and changed the aquaculture licence volumes both up and down in the first period.

The period was characterised by significant disease challenges (the bacterial diseases Vibriosis and cold water vibriosis/Hitra disease) which were treated with antibiotics, which in turn led to a sharp increase in antibiotics use during the period. The sites were more sheltered and shallower than today, and excess feed and fish faeces piled up under the cages, and could cause problems for both farmed fish and benthic fauna.

[22] See also Asche and Oglend (2016).

There is very little information on production costs from the first decade. The Official Norwegian Report of the Lysø Committee carried out an analysis of the profitability of fish farms of the time based on figures from 1974 (NOU 1977:39). It was not until 1982 that the Directorate of Fisheries began publishing profitability surveys for fish farms. [23]

Productivity growth 1985–2005

In the period from the 1980s to the mid-2000s, production costs fell. This development was driven by strong productivity growth, innovations and scale effects (Tveterås, 1999; Asche et al., 2013a; 2013b; Aferweki et al., 2022). The licensing rounds in the late 80s brought with them increased permitted cage volume, number of companies, increased smolt release, increased use of dry feed.

Liberalisation of the rules for hatchery licences in 1985 resulted in growth in new establishments of smolt production (land phase of the production cycle). Combined with several ongrowth licences (sea phase of the production cycle) in the latter half of the 1980s, salmon production increased significantly, which had some negative consequences for the Norwegian aquaculture industry, effects that lasted for decades afterwards. The increase in production resulted in export growth, which in turn led to a significant fall in prices that resulted in dumping accusations from competing fish farmers in exporting countries. Especially Irish, Scottish and North American farmers were active. In the US, a punitive duty of 27% was introduced in 1991, which lasted for 20 years. Over a 20–25 year period, repeated accusations were made against Norwegian fish farmers, which led to an extensive and protracted trade conflict with the EU, which impacted production regulations and licensing in this time period.

In 1991, the ownership restrictions for ongrowth licences were liberalised, and the result was a comprehensive consolidation of the industry where approximately 2/3 of the companies were acquired and incorporated into ever larger companies, providing opportunities for economies of scale. As a result of the sharp increase in production in the 80s and trade problems in the EU/US, a halt to new licensing rounds was introduced in 1989. It was not until 2002 that new permits were announced. Despite the licensing halt in the 90s, productivity improvements continued with new vaccines against the bacterial diseases vibriosis, cold water vibriosis and furunculosis, the use of larger and more robust cages and the use of more exposed sites[24]. The annual production of salmon and rainbow trout increased by approximately 33,000 metric tonnes (~11%) between 1990 (start of license moratorium) and 2002 (end of license moratorium), totalling almost 400,000 metric tonnes. Falling prices made salmon available to new customer groups (Asche and Bjørndal, 2011), which resulted in strong, but varying, demand growth. The low prices of the early 1990s and 2000s resulted in two extensive waves of bankruptcy, which strengthened the rate of consolidation (Asche et al., 2013; Misund, 2017; Zhang and Tveterås, 2022).

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[23] The analysis was conducted by Leidulf Berge at the Institute of Fisheries Economics, NHH. Data were obtained from the Directorate of Fisheries' questionnaire for fish farming in 1974 in addition to supplementary information from fish farmers, a total of 53 facilities.

[24] Hatchery production was liberalized as early as the 1980s, and led to a sharp increase in smolt production, which in turn was also used as an argument for increasing the number of ongrowth fish permits.

Cost growth period 2005–2020

In the mid-2000s, productivity growth fell and slowed the fall in production costs (Vassdal and Holst, 2011; Asche et al., 2013a; 2013b). Since a cost trough was reached in 2005, production costs have been on a rising trend. Between the bottom in 2005 and 2020, the average production cost has increased by 102 per cent in real kroner, and about 63 per cent since 2012 when the MAB limits were reached. This corresponds to a cost increase of 6.3 per cent per year (8.7 per cent in nominal terms). Between 2005 and 2020, prices increased by NOK 19.65 (NOK/kg gutted weight, fixed 2020-NOK), while costs increased by NOK 18.08/kg, so that the industry operating margin in 2020 was lower than fifteen years earlier.

The period after 2005 is characterised by tightening of regulations, especially environmental regulation. In 2005, the size of aquaculture licences was changed from being determined by maximum water volume and feed quotas to maximum permitted biomass (MAB). At the same time, MAB limits were established at various levels; site, company and consolidated company. A standard permit was 780 tonnes MAB in most counties and 945 tonnes MAB in Troms and Finnmark. Since then, the MAB system has been changed several times, e.g. temporary schemes such as the Bremnes model, MAB adjustment after the Crimean invasion in 2015, and a 5 % increase in MAB for fish farmers in Troms and Finnmark in 2011 and the whole country in 2015 with an extra low lice limit. In 2017, a more permanent, systematic and predictable system for production growth was introduced. The traffic light system (TLS) divides the coast into 13 production areas (Pas), which are coloured red, yellow or green according to the level of environmental impact. The TLS was intended to be modular, where new environmental indicators would be introduced successively. Today, only salmon lice-induced mortality on migrating smolts of wild Atlantic salmon is used as environmental indicators. Assessments in TLS are made every two years, and determine whether fish farmers in the production areas are allowed to increase the MAB by 6% (green) or receive an MAB drawdown of 6% (red areas). There are no adjustments in yellow areas. So far, 3 upward adjustments have been made in green areas and 2 rounds of drawdowns in red areas. Various *ad hoc* adjustments and the impacts of TLS adjustments have meant that there is no longer a standard size for aquaculture licences. [25,26]

The MAB system is not the only way the industry is regulated. There are a large number of laws, regulations and other forms of regulation of aquaculture activities (Solås et al., 2015; Robertsen et al., 2016; Osmundsen et al., 2017). Changes (tightening) have been made to existing regulations and a number of new regulations have been introduced over time (see Appendix 1). In the last 15–20 years, tightening of regulations has increasingly been motivated by environmental and fish health considerations (Osmundsen et al. 2017; Greaker et al., 2020; Osmundsen et al., 2020; Larsen and Vormedal; 2021; Osmundsen et al., 2022;), also abroad (Anderson et al., 2019). Examples of environmental and fish health regulations that have been tightened are:

[25] See article by Bjørn Hersoug (Hersoug, 2021; 2022), Tveterås et al. (2020) and Robertsen et al. (2020a, 2020b) for more information about regulations and about the changes in the licensing regime over time.
[26] https://www.hi.no/hi/nyheter/2020/februar/trafikklys

1. **Lice level.** The Lice Count Regulation regulate the permitted number of mature female lice per farmed salmon. The regulation was introduced to reduce the spread of salmon lice from aquaculture to wild salmonids. The Lice Count Regulation was first introduced in 1998, but later amended a number of times (see Figure 5 and Appendix 1). The first regulations set the lice limit at 2 sexually mature female lice in the spring and 5 the rest of the year. The number of salmon lice was to be counted every two to four weeks, and with mandatory delousing only if the lice limits were exceeded. Gradually, the regulation was amended towards more frequent measurements, lower lice limits, and changes in when delousing should take place (from the requirement for mandatory delousing *after* the lice limit has been reached to *before* lice limits have been reached). In addition, there are extra strict lice requirements for so-called special green permits and to be able to come under exemption provisions in the traffic light system. Under current rules (2013 regulations), a maximum of 0.5 mature female lice per farmed salmon is allowed, with the exception of a 6-week period in the spring when the limit is 0.2 (in the period when smolts of wild salmon migrate from rivers to the sea).[27]

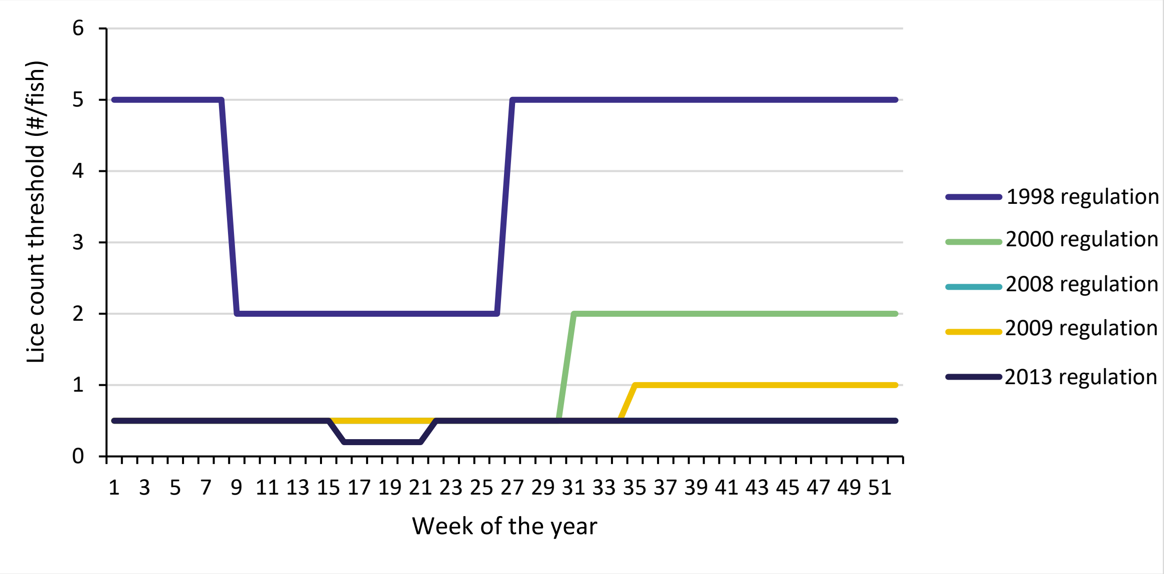

Figure 5. Lice boundaries over time for South Norway. Source: Lovdata.

2. **Distance requirements between localities.** Requirements for minimum distances between sites have been introduced for reasons of spread of infection / biosecurity. The requirements are not laid down in separate regulations, but in one of the Norwegian Food Safety Authority's guidelines, and set limits for how close farming site can be to each other. The distance requirements have become stricter over time. In the 1970s and 1980s, a distance requirement of 200 metres was practised, later increased to 500m and 1000m in the latter half of the 1980s. Today, the requirements are 2.5 and 5 kilometers distance

[27] The last change was introduced in 2013.

between sites depending on size. Distance requirements have also been introduced to harvesting plants and for national salmon fjords (see also appendix).[28]

3. **Technical standard.** The NYTEK regulations regulate the technical standard of facilities and are motivated by escapee prevention. The regulations were first introduced in 2003, and have subsequently been amended in 2012 (NYTEK12) and 2023 (NYTEK23). [29,30]

4. **Maximum permitted biomass (MAB)**. The MAB system was introduced in 2005 and replaced regulations that limited the size of permits based on water volume and feed quotas. In the twenty-year period after the deliberalisation of smolt production in the mid-80s, the Norwegian aquaculture industry was repeatedly reported to the American and European competition authorities (anti-dumping accusations). Changes in the license regulations during the period (including the MAB system) were therefore mainly motivated by a goal of avoiding overproduction (market considerations). Over time, environmental impact has become an increasingly important regulatory consideration (environmental and fish health considerations). In order to meet changing considerations, the MAB system has been changed in various temporary and permanent versions, such as extra low lice requirements from some green permits and to come under exemption provisions in the traffic light system. The traffic light system is based on the MAB system, but regulates changes in MAB up or down based on estimated lice-induced mortality on migratory post-smolt of wild Atlantic salmon. The fact that the authorities are reluctant to use new capacity and new sites for environmental reasons will also be an indirect form of environmental regulation.

1.1. Profitability in aquaculture is highly cyclical

Profitability in the aquaculture industry is cyclical, as is common in other commodity industries (Figure 6). The operating margin has varied between -10 and +35 per cent on average but increased over time.

[28] The Norwegian Food Safety Authority's guide «Establishment applications – case processing in the audit»: Establishment applications - case processing by the Authority (mattilsynet.no).
[29] Regulations relating to requirements for technical standards for facilities used in aquaculture/aquaculture.
[30] Regulations relating to requirements for technical standards for aquaculture facilities for fish in the sea, lakes and waterways https://lovdata.no/dokument/SF/forskrift/2022-08-22-1484.

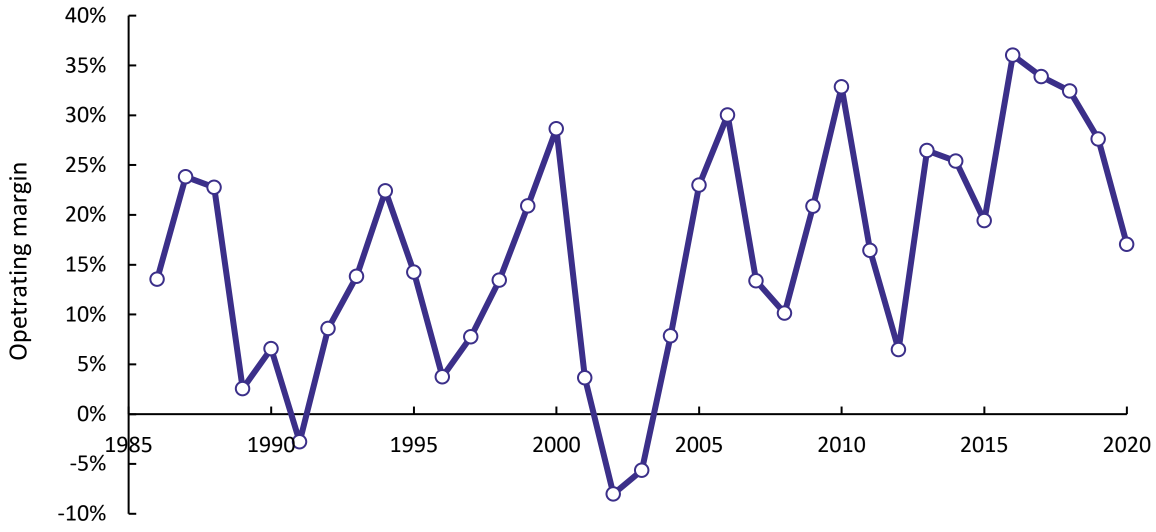

Figure 6. Average operating margin 1986–2020. Source: Norwegian Directorate of Fisheries.

However, the operating margin does not provide a complete picture of the profitability of the aquaculture sector. An important cost element is omitted, namely the cost of capital. Economic *profit* is a term that also includes the cost of capital (price of the opportunity use of the capital invested in enterprises). Popular profitability measures such as *return on* equity include financial costs, but omit the cost of equity, and neither profitability margins nor returns on capital are perfect measures of profitability. Figure 7 shows economic profitability as a percentage of turnover, and here capital costs are deducted. Economic profit as a percentage of turnover has varied between -20% and +25%. In 2020, the industry as a whole ran a financial deficit. Over the past 2 years, profitability has risen again, and going forward there is no reason to believe that profitability will not continue to fluctuate from year to year.

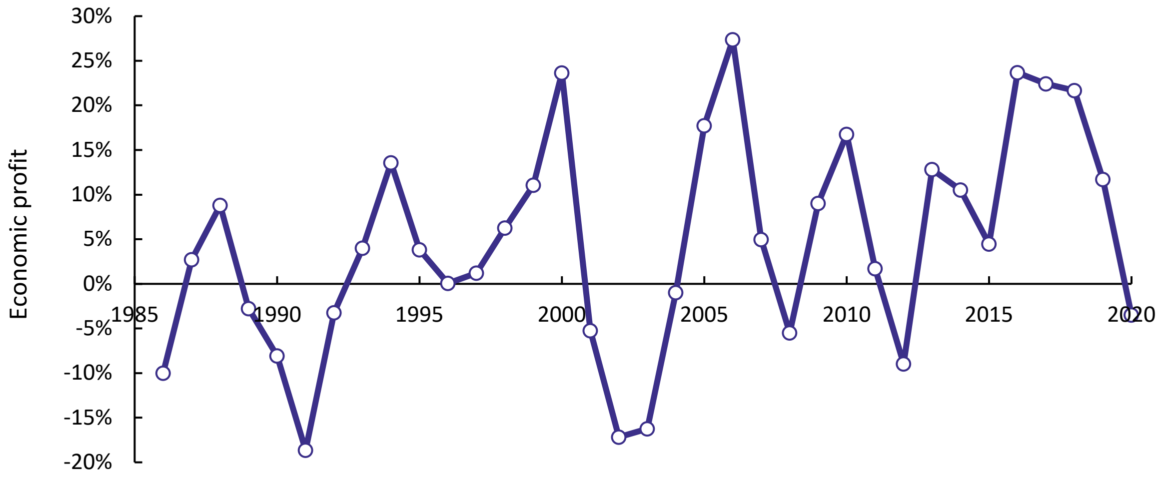

Figure 7. Economic profitability (percent of turnover) 1986–2020. Source Directorate of Fisheries.

1.1.1. Profitability and economic rent

Since 2005, the average profitability margin has been higher than in the period before 2005 and resulted in extraordinary profitability that has been substantial in periods. The large profits, in addition to increased market prices for aquaculture licences, are an indication that there is an economic rent in aquaculture (see also NOU 2019:18; Misund et al., 2020; Misund and Tveterås, 2020). [31,32]

There are various concepts of profitability in economics, such as economic profit, accounting profit, producer surplus and economic rent (see Arnason and Bjørndal, 2020). In simple terms, economic rent can be defined as an extraordinary profit generated by some form of scarcity, e.g. scarcity of input factors such as permits/licenses, sites, etc. Extraordinary profits (also called extraordinary returns, pure profits or super profits) are profits in excess of a normal return. In principle, the normal return is the same as the sum of operating and capital costs (including equity costs).

In a theoretically simplified model, all extraordinary profitability can be attributed to a single input factor that is scarce, and if the scarce factor is a natural resource then the extraordinary profits can be called a resource rent. However, profitability in aquaculture will be a function of price as well as a number of input factors, some of which may be scarce in the shorter or longer term (see Arnason and Bjørndal, 2020), and give rise to various forms of economic rents.

If it is nature itself that determines the scarcity, then the extraordinary profits can be called a resource rent. In aquaculture, a shortage of sites can result in a resource rent to the extent that nature determines the scarcity. But if it is the authorities that set the restrictions, then it is a regulation or policy rent, not a resource rent. In most salmon and rainbow trout producing countries, stricter environmental regulations have led to weaker output growth over the past 10–15 years[33]. In Norway, the authorities have long been reluctant to award new licenses, and over the past 10 years capacity adjustments are directly linked to performance on environmental indicators. In addition, the scarcity of sites is mainly determined by minimum distance requirements. In the 1980s, fish farms could be placed with minimum distances of 200 meters, whereas today the distance requirements are 5 km.

Extraordinary profits can also be due to cost differences between companies. We call this inframarginal rents, which is a collective term for different forms of economic rents caused by cost differences. There can be various reasons behind the cost differences. If some companies are more efficient and skilled than other companies, this may give rise to a skill rent (possibly investment or entrepreneurial rent), also called skipper rent in the fisheries economics literature. If some sites are better and more productive than others, this can give rise to a differential rent, which is a form of a resource rent.

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[31] In a Norwegian context, the term ground rent (“grunnrente”) is often used to refer to extraordinary profitability, but the term economic rent is more precise and what is used in the modern economics literature. Economic rent is an umbrella term and there are, however, different opinions among economists as to whether the economic rent is purely a resource rent (Greaker and Lindholt, 2022) or a combinatrion of regulation rent and other rents (Asche et al., 2020; Arnason and Bjørndal, 2020; Misund et al., 2019c; Oglend and Soini, 2020; Misund and Tveterås, 2020a; 2020b).

[32] For more information on prices, profitability, values and volatility, see Asche and Misund (2016), Asche, Misund and Oglend (2016a; 2016b; 2016c; 2018; 2019), Misund (2016; 2018a; 2018b), Misund et al. (2018), and Misund and Nygård (2018).

[33] Some Economists refers to this regulatory rate as a concession rent.

Some forms of economic rent may be temporary, and are called quasi rents. Economic rent is therefore a collective term for three types of interest rates;

1. Scarcity rents (resource, regulatory rents, etc.)
2. Inframarginal rents (skill rents, etc.)
3. Quasi rents (temporary)

The meaning of the Norwegian term "grunnrente" is often unclear and will have varying definitions. According to Store norske leksikon and in Greaker and Lindholt (2022), "grunnrente" is set equal to resource rent. In the public debate, it seems that most people also use a similar definition of "grunnrente"[34], i.e. an excess return associated with the exploitation of natural resources. In the NOU 2019:18 White Paper, on the other hand, "grunnrente" is used to refer to pure profits, i.e. all extraordinary profits. Many researchers (eg. Arnason and Bjørndal, 2020; Misund et al. 2020; Misund and Tveterås, 2022) are critical of such a definition, which also deviates from the definition in SNL and the common perception of the term.

Extraordinary profits in aquaculture will include several forms of rents, both scarcity, inframarginal and quasi rents. In practice, it is therefore a very challenging task to identify and isolate a specific form of rent, and then tax it separately. Attributing all extraordinary profits to only resource rent is not academically incorrect (see Arnason and Bjørndal, 2020; Misund and Tveterås, 2020), and in practice profit-based or cash flow-based resource rent taxes become special taxes (i.e. indiscriminate taxes on profits, not rents).

Recent economic literature points out that the extraordinary profit in salmon aquaculture is mainly due to stricter environmental and fish health regulations in Norway and other production countries (Arnason and Bjørndal, 2020; Misund and Tveterås, 2020; Oglend and Soini, 2020; Asche et al., 2022b; Estay and Stranlund, 2022; Afeweki et al. 2022). The authors refer to the extraordinary surplus as a *regulation or policy rent*, not a resource rent. When it is environmental regulations that give rise to an economic rents, it is not obvious that it should be taxed in the same way as a resource rent (see e.g. Oglend and Soini, 2020).

1.2. Theme of this report

This report will not cover all aspects of production costs and developments over time, but will focus on biological costs as there is limited knowledge about these. For more information about other cost drivers, please refer to Nofima and Kontali's analyses: [35]

The final report by Iversen et al. (2019) summarises a number of studies on cost developments in Norwegian salmon farming conducted by Nofima and Kontali. The researchers have thematically looked at Norway vs. competitor countries (Iversen et al., 2019b; 2020), smolt costs and capital (Iversen et al., 2018), and feed and lice costs (Iversen et al., 2017). Iversen et al. (2019) concludes

[34] https://snl.no/grunnrente
[35] See https://www.fhf.no/prosjekter/prosjektbasen/901115/ and https://www.fhf.no/prosjekter/prosjektbasen/901335/.

that feed costs have accounted for the largest cost increase in NOK, driven by increased feed prices and feed conversion rate. They also find that smolt costs and depreciation have increased considerably over the past 10 years. The smolt cost increase is driven by a transition to larger smolt and investments in RAS facilities, while the increased depreciation is due to increased capital intensity in the industry, which is also documented by Blomgren et al. (2019). [36]

Iversen et al. (2019) also points to the cost item "other operating expenses", which has increased considerably over the past decade. An important reason is that some of the operations previously carried out by fish farming companies have been outsourced to specialised companies, such as wellboat companies. In addition, lice costs have increased significantly. Nofima and Kontali have calculated that the direct lice costs cost the industry around NOK 5 billion per year. The direct costs consist of equipment such as lice skirts, starving, mortality from treatment, cleaner fish, lice treatment, drugs and lice operations. The indirect costs come in addition to the direct costs, but very few studies have looked at this (see e.g. Abolofia et al., 2017 and Asche et al, 2022). In 2011, salmon lice cost approximately NOK 4 billion corresponding to 9 per cent of sales revenues (Abolofia et al., 2017). Biomass loss was approximately 3.62–16.55%. A recent unpublished study using the same methodology finds that costs have increased to 14 per cent of turnover, corresponding to a cost of NOK 12 billion per year given the production and salmon prices in recent years. In addition, there are costs from disease outbreaks. However, there is only one known estimate of disease costs (Vedeler, 2017). He found that the largest viral diseases cost the industry NOK 4.2 billion in 2015. As mentioned, it is difficult to distinguish the pure disease costs from the lice costs, which makes it difficult to summarise the estimates of lice and disease costs. In addition, the estimates of Iversen et al. also include. (2017; 2019a) starvation and direct mortality, factors that will also be included in the estimates of indirect lice costs. Common to these studies is that they do a "bottom-up" analysis. This report uses a different approach, providing an aggregated estimate of the biological costs associated with lice, disease, stress, etc. The disadvantage of the method is that it is not possible to distinguish between lice and disease costs, but as mentioned, this is nevertheless very difficult to achieve in practice.[37]

[36] See also Iversen et al. (2015).
[37] A similar analysis was carried out by Geir Inge Rødseth in Stingray (Rødseth, 2016): https://www.linkedin.com/pulse/behandling-mot-lakselus-kan-ha-kostet-7-8-milliarder-kroner-r%C3%B8dseth/?originalSubdomain=no. He also subtracts lost profits and finds a total cost of 7–NOK 8 billion for 2015.

2. What is included in the farmers' production costs?

2.1. Composition of the cost of production

The analyses in this report are based on the Directorate of Fisheries' annual profitability surveys for ongrowth farming of salmon and rainbow trout. In its annual survey, the Norwegian Directorate of Fisheries has collected information on the various components that are included in the total production costs, such as feed, wages, smolt, etc. Up to and including 2008, the cost calculations also included cost of equity, but with the change to a more financial economic perspective, these were no longer included. The cost of capital, however, tells us something about the opportunity cost of capital, and is therefore an important cost element that should be included in calculations of total production costs. In the analyses below, the cost of capital is calculated separately based on the calculated total assets (total assets) and a nominal required rate of return of 8 percent.

Production costs for farmed salmon and trout can be calculated on the basis of different times of slaughter, and it is important to distinguish between live fish weight, whole fish weight and gutted weight. Live fish weight (*LW)* is the weight of the fish before starving and bleeding (6–8 per cent weight loss) [38]. Subtracting these weight losses gives whole bled fish or *whole fish equivalent, WFE).* The Directorate of Fisheries uses whole fish weight as a standard measure, as does FAO in its figures for aquaculture production. Gutting results in an additional 10% weight loss. *Head on gutted (HOG)* is the weight measure used for salmon prices, both by Statistics Norway and Nasdaq. Gutted weight is also preferred by financial analysts. Trout and Coho will have different conversion factors than Atlantic salmon. In this report, conversion factors from Norwegian Standard NS 9417:2012 will be used.

The different ways of measuring fish weight can create confusion, and for this reason it is important to be careful when talking about salmon prices and costs. In this report, the costs will be reported per kilo gutted weight as it will be easier to compare with market prices for Atlantic salmon and rainbow trout, but can easily be converted to whole fish weight. Table 1 shows production costs with different weight measures.

[38] See e.g. Kontali's conversion factors: https://www.kontali.no/uploads/EgGg52fr/demo-Monthlysalmonreport.pdf.

Table 1. Composition of production costs for salmon and trout farming 2020. Costs other than capital costs are calculated by the Directorate of Fisheries. The cost of capital is calculated from total assets and a nominal required rate of return of 8 percent. The conversion factor between whole fish weight/gutted weight is 1.125, and between gutted weight and live weight is 1.215.[39]

NOK/kg	Live Weight (LW)	Whole fish weight (WFE)	Gutted weight (HOG)
Smolt cost	3.83	4.14	4.66
Feed cost	15.39	16.62	18.69
Insurance cost	0.15	0.16	0.18
Labour costs	2.98	3.22	3.62
Depreciation	2.45	2.64	2.97
Other operating expenses	8.99	9.71	10.92
Operating costs sea phase	**33.79**	**36.49**	**41.04**
Cost of capital	7.20	7.78	8.75
Production cost sea phase	**40.99**	**44.27**	**49.79**
Harvest and packing cost	3.75	4.05	4.55
Production cost harvested	**44.74**	**48.32**	**54.36**

The Directorate of Fisheries also reports insurance costs. These are relatively small and will be included in the rest of the report in the item other operating expenses. Furthermore, the net financial cost is replaced by a separate cost of capital. Net finance is calculated as financial expenses minus financial income divided by production. Since 2016, this has been negative for the industry as a whole, due to the fact that the debt ratio and interest rates have fallen and that the companies have significant financial income. In financial economics, it is common to distinguish between operations and financing, and in Table 1 the term operating cost sea phase is used for the part of the unit cost associated with operations, production cost *sea phase* includes capital costs, while *total production cost* includes harvest and packing costs. The cost of capital is an important cost that is often omitted in analyses of costs in aquaculture. Invested capital in the industry has increased over time, and the cost of capital has therefore become an increasingly important cost element. The production cycle is long, and investments in biomass will only be realized at the time of slaughter. Meanwhile, smolt, feed and other services have been purchased. In principle, this money could have been invested in something else that would have yielded a return. This alternative return must be taken into account when calculating production costs.

[39] There will be different conversion factors for salmon and rainbow trout, but here it is used for salmon since the production of salmon dominates.

A common way to calculate capital costs is to multiply capital by a required rate of return. Here, measurement errors will potentially occur. In principle, market values of capital should be used, but with the exception of stock exchange listed companies, the market values are not known or easily estimated. Book values must then be used, either total assets or other forms of capital calculations such as capital employed. Furthermore, one must use a required rate of return, typically one will prefer a weighted required rate of return after tax (WACC). The next problem will be calculating WACC. Typically, one will use the capital asset pricing model and WACC formulas from the textbooks, but since expectation values are to be used in these, measurement errors will occur since expectations cannot be easily measured. In principle, the required rate of return should reflect the contribution risk from a project to total systematic risk in the company, but this is impossible to calculate in practice since it is not possible to measure this future risk. The theoretically calculated required rates of return (based on historical analyses) will typically be several percentage points below the required rate of return used in practice. An analyst will therefore often resort to a standard required rate of return. In aquaculture, such a requirement will typically be 8 percent or higher. In the oil industry, high required rates of return, 10–20% and above, are used, depending on the project. In this report, the cost of capital will be calculated as the product of a required rate of return of 8 per cent and average total assets throughout the year.

The "other operating cost" item is the second largest cost. According to Iversen et al. (2015; 2017; 2019) this record contains the following components:

- Contracted services
- Net cleaning and treatment
- Administration
- Maintenance
- Health costs
- Energy and transport
- Control, lice counting
- Treatment costs
- Cleaner fish

In addition, the Directorate of Fisheries states that the cost item contains income and expenses from other activities. In recent years, the Directorate of Fisheries has started reporting the composition of «other» operating costs (Figure 8). Other operating costs jumped from ~4 NOK/kg in 2010–2012 to ~8 NOK/kg in 2013–2015, and have varied between NOK 8 and 11 per kg in the period 2016–2020. Compared to 2010–2012, other operating expenses have increased by 2–3 times. Since the composition before 2015 is not known, it is difficult to assess which of the components "Fish health", "Environment and maintenance" or "Other" has been the most important driver. In the period 2015–2020, direct fish health costs have represented approximately 25% of other operating costs.

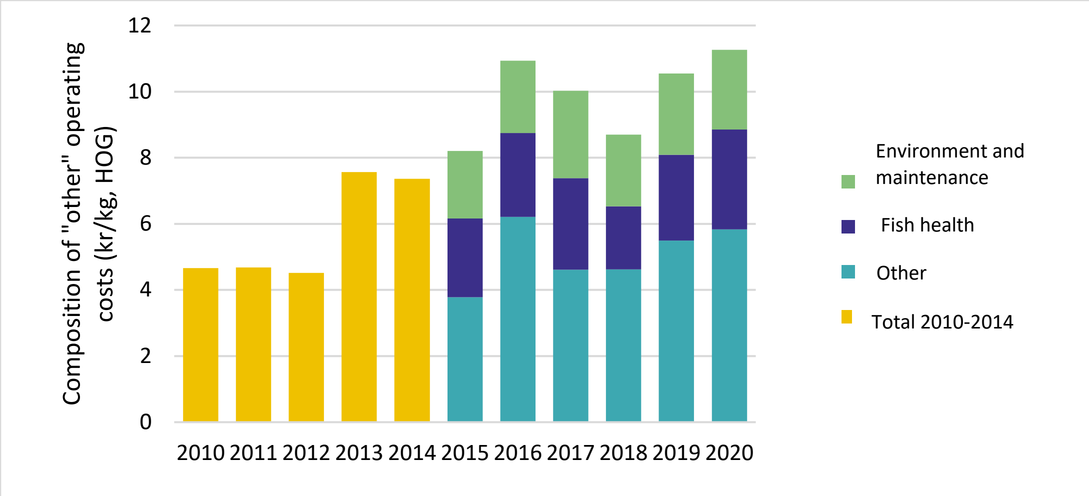

Figure 8. The composition of «other» operating costs (2021-NOK, gutted weight). Source: Directorate of Fisheries.

The composition of production costs has changed considerably over the past 10 years (Figure 9). The figure shows that feed costs have increased the most measured in NOK. Since the cost bottom in 2005, all cost elements have increased, especially feed, other costs and capital (cost of capital and depreciation/depreciation) (Figure 9). Table 2 shows changes in costs per kilo and in per cent.

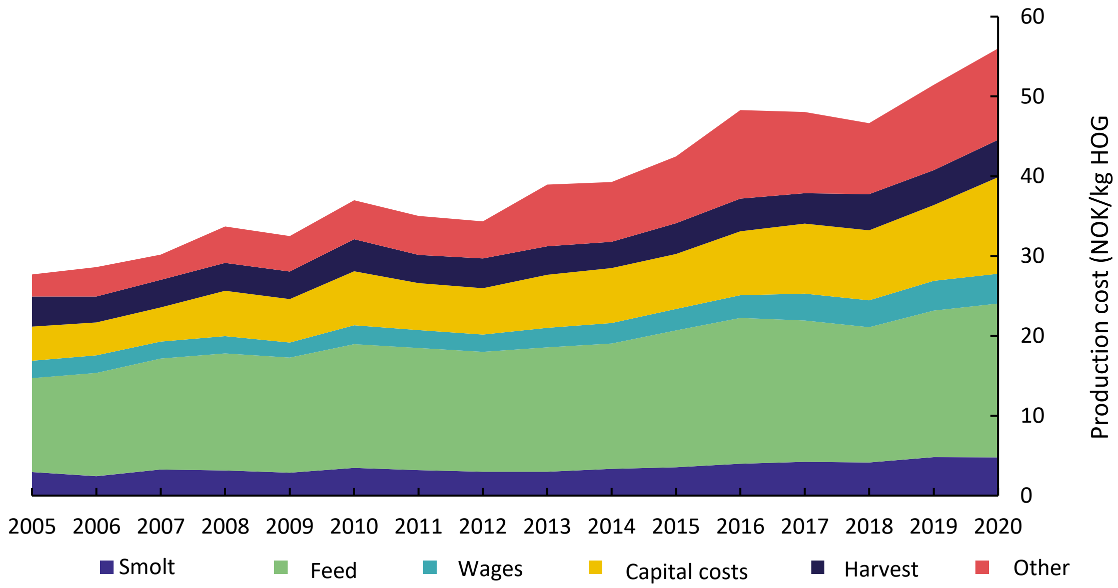

Figure 9. Composition of production costs for salmon and trout 2010-2020. All figures are inflation-adjusted

(2021-NOK). Source Directorate of Fisheries and own calculations. The figures are taken from the Directorate of Fisheries' annual profitability surveys and adjusted for inflation. [40]

Table 2. Changes in cost elements (NOK/kg gutted weight). Measured in nominal and fixed NOK and percentage changes. Here is the change measured between 2005 and 2020. Inflation adjustment with the consumer price index 2005–2020.

	Change in NOK		**Change in per cent**	
	Nominal	**Fasting (2020)**	**Nominal**	**Fasting (2020)**
Feed	10.31	7.26	123 %	63 %
Smolt	2.57	1.81	123 %	64 %
Wages	2.07	1.51	134 %	71 %
Depreciation	2.04	1.70	219 %	134 %
Other operating expenses	9.16	8.45	469 %	317 %
Operating costs sea phase	**26.15**	**20.73**	**175 %**	**102 %**
Cost of capital	6.64	5.87	314 %	203 %
Production cost sea phase	**32.79**	**26.60**	**193 %**	**115 %**
Harvesting	1.86	0.89	69 %	24 %
Production cost harvested	**34.65**	**27.49**	**176 %**	**102 %**

However, such a representation does not provide us with sufficient information if we want to analyze the drivers of increased feed costs. We see that feed costs have increased by NOK 7.26/kg (in fixed 2020-NOK), but do not tell us whether the reason is i) increased prices for input factors in the feed (e.g. soy, wheat, etc.), ii) krone depreciation, iii) increased costs in the production of feed in excess of the price of input factors, iv) reduced utilisation of feed in farmed fish (e.g. disease, starvation, etc.), or v) increased mortality in the ongrowth farming phase. All these factors can increase the cost of feed at the farmer. The first three will increase the purchase price of feed while the last two factors will increase the feed conversion rate. Later in the report, the effect of changes in economic feed conversion rates will be used to isolate the effects of biological challenges. One

[40] Production of Atlantic salmon and rainbow trout (not quantity of harvested fish) measured in gutted weight is used as a denominator. «Feed» are costs per kilo of salmon and trout produced. «Smolt» are costs for purchasing hatcheries and «Wages» are labor costs. On the capital side, «Capital depreciation» depreciation per kilogram and «Capital» cost of capital. «Harvest» is the harvesting and packing cost as reported to the Directorate of Fisheries. «Other» is the collection item other operating cost per kilogram. Other operating expenses also include insurance costs.

can then distinguish between an increase in feed costs due to increased feed prices from that caused by inefficiencies, including costs from biological risk.

Cost of harvesting accounted for the smallest increase, both in fixed NOK and in per cent. The reason for this is not entirely known. One possible explanation may be that biological problems affect costs in the sea phase, but not the fish that are slaughtered, as only live fish are harvested. All cost elements are divided by the same denominator (production), and the latter is calculated on the basis of the quantity sold and inventory of live fish, i.e. dead fish are kept out. Feed, smolt, wages, capital depreciation and "other" operating costs are costs incurred for both live and dead fish, but harvest costs are only incurred for live fish that are slaughtered. Increased mortality and especially mortality of large fish will increase operating costs in the sea phase more than harvest costs, all other things being equal. Another reason may be reduced costs due to investments in more cost-effective harvesting and processing plants.

Different rates of change have changed the composition of production costs over time (Figure 10). Although feed costs have increased the most measured in NOK, their share of the total cost has decreased. Capital depreciation (depreciation) and capital costs, as well as other operating expenses, have increased their shares.

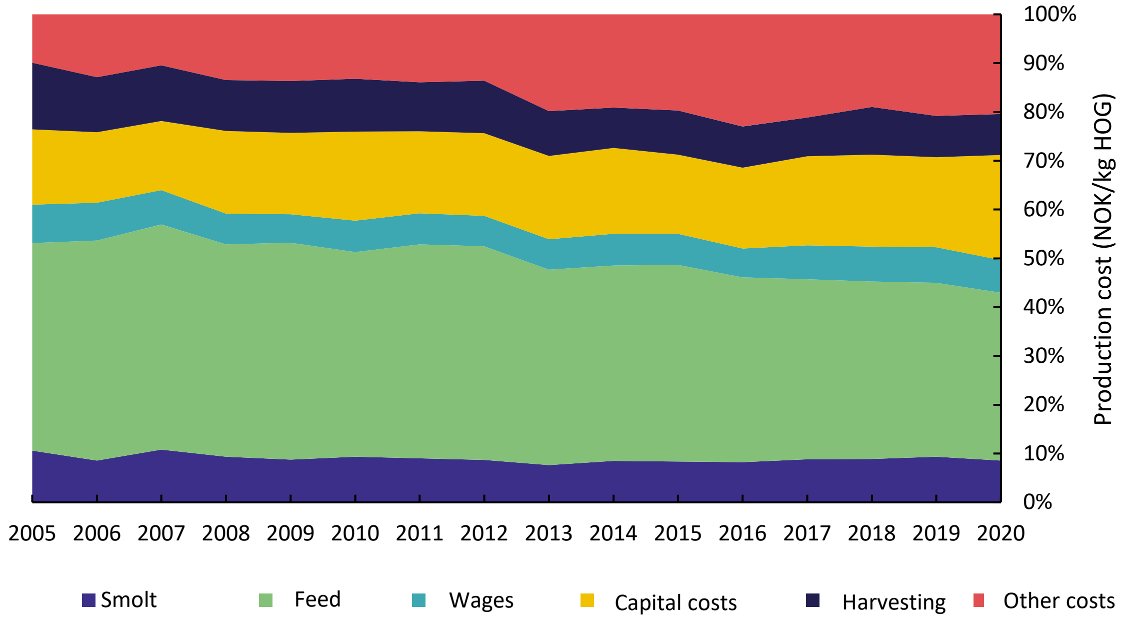

Figure 10. Changes in cost components 2005–2020 (2005=100). Source Directorate of Fisheries and own calculations.

2.2. Composition of the cost of feed

As mentioned earlier, the increased feed cost may have several causes. In this section, we will take a closer look at important drivers behind the increase in feed costs, such as increased prices for feed components (soy, wheat, rapeseed oil, etc.), depreciation of the krone, and less efficient use of the feed.

Feed is the single most important component of the cost of production. The feed cost per kilogram is calculated as the sum of the value of feed in stock at the beginning of the year plus the purchase of feed minus the value of feed in stock at the end of the year, divided by the production during the year. Production refers to the biomass of salmon and rainbow trout that was built during the year, and this is not the same as the quantity harvested and sold (harvest quantity) in a particular year. The feed consumption (numerator) is equal to the product of the amount of feed (kg) and the feed price (NOK / kg).

$$Feed\ cost = \frac{(YB_{Feed} + Purchase - YE_{Feed})}{Production} = \frac{Feed\ use}{Production} = \frac{Feed\ amount \cdot Feed\ price}{Production} \tag{1}$$

Annual cost averages do not provide a complete picture of what it costs to feed the smolt to harvest size. First, costs are best measured over an entire production cycle and per generation/cohort. A production cycle lasts up to 18 months, while the feed cost is reported annually, across cohorts/generations. Secondly, feed consumption is distributed over the amount of live fish produced, i.e. changes in live/whole fish weight over the year. Fish that have been fed and have died are not included in the production. Furthermore, stress, disease, starvation (e.g. lice treatment) will lead to reduced growth. Increased feed waste will increase the amount of feed used without leading to production, as will feed eaten by cleaner fish. Feed costs will therefore increase with increasing deviations from optimal fish growth conditions.

The feed conversion rate is defined as $FCR = \frac{Feed\ amount}{Production}$, and gives

$$Feed\ cost = \frac{Feed\ amount \cdot Price}{Production} = FCR \cdot Feed\ price \tag{2}$$

And with feed price quoted in USD, the relation becomes:

$$Feed\ cost\ (NOK) = FCR \cdot Feed\ price\ (USD) \cdot NOK/USD \tag{3}$$

In simple terms, changes in feed cost can be broken down into three key drivers; i) feed conversion rate, ii) prices of the feed on the international market, and iii) exchange rate. Feed costs measured in NOK will increase with an increased feed conversion rate, higher feed ingredient prices and a depreciation of the Norwegian krone against the USD.

In the following, these three variables will be examined, first developments in prices in the international commodities markets, then the effect of the depreciation of the krone and the changes in feed conversion rate. Later, the feed conversion rate will be used as a starting point for analyzing inefficiencies, which can represent a measure of biological costs.

2.3. Prices of feed ingredients

The main feed ingredients are soybean meal, soybean oil, rapeseed oil, wheat, corn, fish meal and oil (Misund et al., 2017; Aas et al. , 2019). Over time, the proportion of marine raw materials has been reduced in favour of an increased use of vegetable raw materials. The price formation for agricultural raw materials occurs mainly in international commodities markets, quoted in USD.

Figure 11 shows the development of the main agricultural raw materials used in salmon and trout feed, measured in USD and indexed to 100 in 2005.

Feed ingredient prices rose between 2005 and 2008, fell between 2009 and 2010 before rising again towards 2012. Since then, prices for agricultural raw materials have fallen, while fishmeal has fallen far less. The fluctuations in prices for agricultural raw materials have largely followed the two boom & bust periods before the financial crisis in 2007/2008 and before the European banking crisis in 2012. In summary, feed ingredient prices have risen between 2005-2012 and fallen between 2012 and 2020. There has also been a significant increase in 2021 and 2022 that are not included in the figures here.

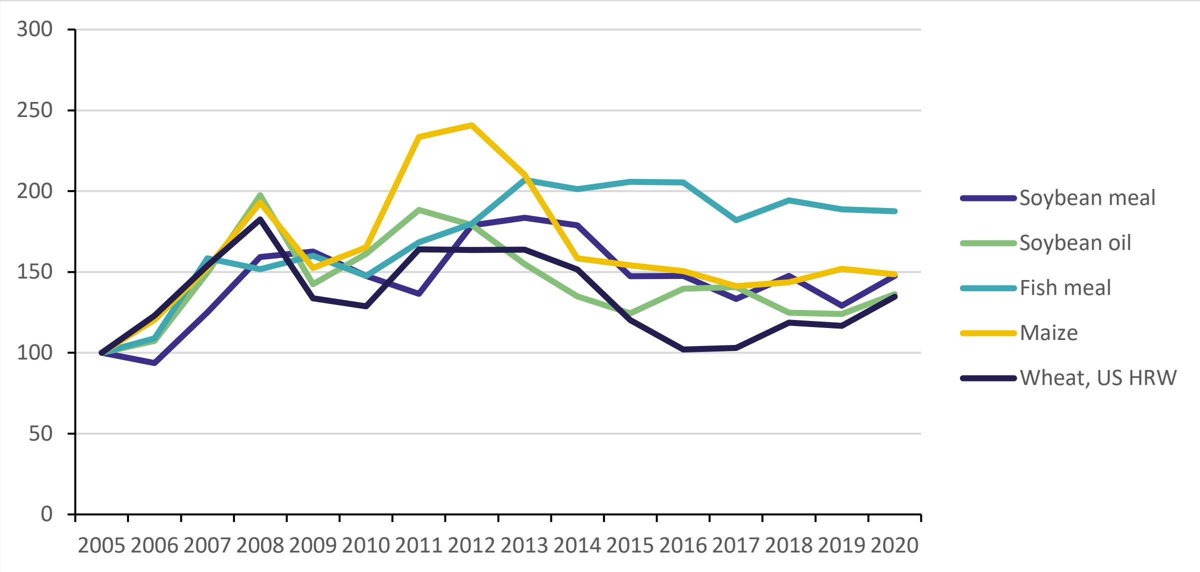

Figure 11. Agricultural raw materials 2005–2020. Indexed (2005=100), based on percentage developments in fixed 2010 USD prices. Source: World Bank

Figure 12 shows feed prices measured in NOK. In contrast to the prices of feed ingredients measured in USD, the feed price measured in NOK has risen in almost all years. The reason why feed prices measured in NOK did not fall after 2012 may be due to currency effects and will be discussed in the next section.

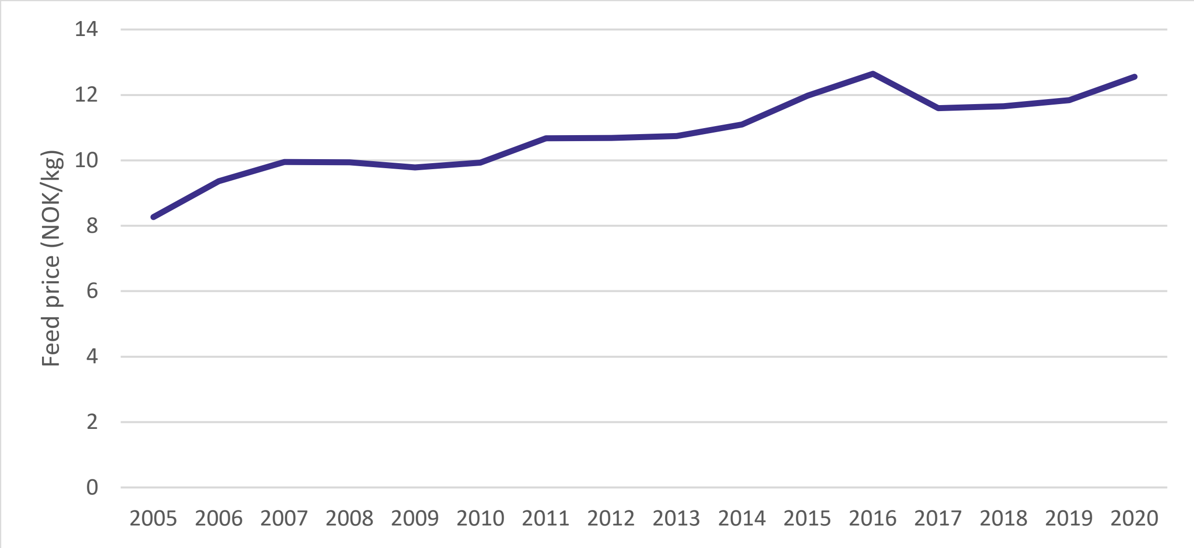

Figure 12. Feed price in fixed 2020-NOK per kg. Source: Directorate of Fisheries' profitability survey.

2.4. Currency effects

A global market for farmed salmon and trout ensures that changes in exchange rates against the most important markets will translate into changes in salmon and trout prices measured in NOK. The same can also be observed on the cost side. Most of the feed raw materials are imported, and prices for soybean meal, soybean oil, wheat, corn, etc. are determined in global commodity markets, typically in USD. The prices of other input factors such as steel, diesel, etc. also have a global price formation. In the period 2005–2020, the Norwegian krone has depreciated against major currencies such as the EUR and USD (Figure 13), particularly after 2014. The depreciation of the krone against the USD is particularly evident. A high NOK/USD means that the price of input factors such as feed ingredients, diesel, and other commodities measured in NOK will be higher than if the krone were stronger. The combination we see today with high commodity prices and high NOK/USD (weak krone) will thus have a particularly strong impact on the cost side for fish farmers.

Figure 13. Development in NOK/EUR and NOK/USD 2005–2022, indexed (2005 = 100).

Figure 14 compares developments in feed prices measured in NOK and in USD. Here, feed prices measured in USD show the same trends as prices for feed ingredients in global commodity markets in Figure 11, which reinforces the impression that a depreciation of the krone is an important reason for the increase in fish feed.

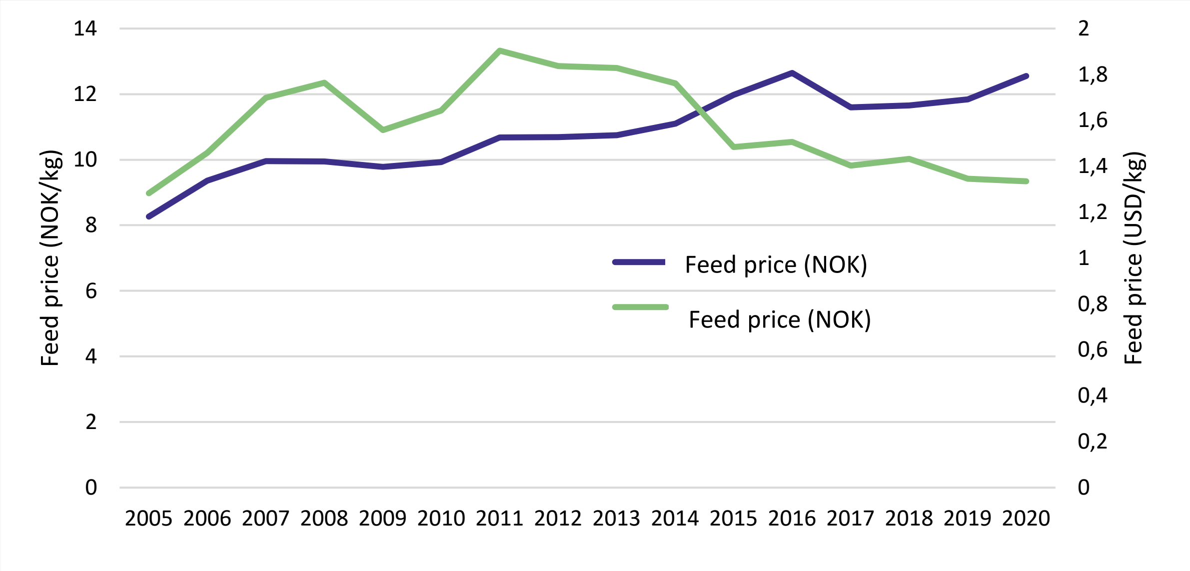

Figure 14. Feed price measured in NOK vs USD. Sources: The Directorate of Fisheries' profitability surveys (feed price) and the Norwegian Central Bank (exchange rates).

The depreciation of the krone has also contributed to other cost increases in aquaculture, but these effects are more difficult to separate out and analyse. Examples include the purchase of foreign goods and services other than feed.

2.5. Feed conversion rate

The feed conversion rate indicates how efficiently the salmon utilise the feed. The feed conversion rate is calculated as the amount of feed divided by production, i.e. how many kilos the fish grow per kilo of allocated feed. [41]*Biological* feed conversion rate (bFCR) is the amount of feed eaten by the fish divided by the amount of fish produced, while the economic feed conversion rate (eFCR) includes only the fish that have survived, and also includes feed waste and escaped fish. Increased use of non-medicinal delousing methods has resulted in increased mortality of large fish. Mortality of large fish will increase eFCR more than mortality of small fish does since more feed has been used to feed a large fish than a small fish. We will see later that the average weight of dead fish has almost doubled since 2010.

The biological feed conversion rate will be influenced by a number of factors such as fish species, light, season, temperature, fish size, growth rate, feed composition (Misund, 1995; 1996; Refstie et

[41] *Feed conversion efficiency* (FCE) is a term used in the literature and is the inverse of the feed conversion rate.

al., 2000; Nordgarden et al., 2003). The feed conversion rate increases with the size of the fish and decreases with the growth rate. Stress, disease, handling, etc. that do not lead to mortality, but reduce the welfare, appetite and growth rates of the fish will also increase bFCR. The difference between eFCR and bFCR rises with increasing mortality, escapees, other production losses and feed waste. There are also two types of biological feed conversion rate, one calculated under laboratory conditions where it is possible to collect feed waste (bFCR-lab) and the biological feed conversion rate calculated at plants in commercial operation (bFCR field). Under these conditions feed waste is not possible to measure effectively. Furthermore, bFCR fields will be calculated based on harvested fish and converted to a biological feed conversion rate based on live weight.

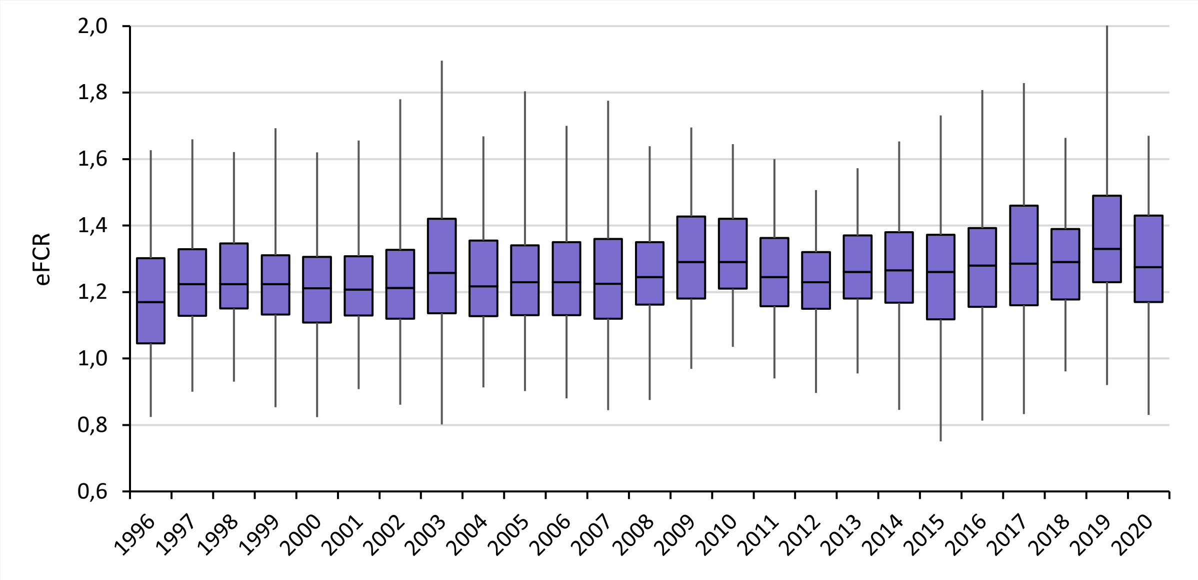

Figure 15. Feed conversion rate. Boxplot (the box contains 50% of the observations, the lines 90%). Source: Directorate of Fisheries' profitability survey. In 2019, the highest feed conversion rates are truncated at 2.0.

Figures from the Norwegian Directorate of Fisheries show a considerable variation in the economic feed conversion rate between fish farmers (Figure 15), from less than 0.8 to more than 2.0. The median feed conversion rate has risen over time, from just under 1.2 in 1996 to more than 1.3 in recent years. Here it is calculated annually but should preferably be calculated over a whole generation as annual figures may be affected by when in the production cycle some smaller farmers have been harvesting their fish. If a small company has fed fish of smaller size, but not harvested, in the same year, the feed conversion rate will be lower than if they have only produced and harvested large fish. For larger companies, this effect will disappear since they have a portfolio of sites and an average figure is more representative. Observations of economic feed conversion rates below 1.0 are not realistic over an entire production cycle.

3. What is the cost of biological risk?

3.1. The feed conversion rate is a measure of inefficiency

As mentioned above, eFCR will be an indirect measure of biological risk. The increase in the category "other operating costs" may also indicate that biological challenges have become more expensive. But how large the increase in biological costs has been and their causes have been poorly examined and analysed. Biological costs are here used as a collective term for costs related to mortality, disease, lice infestations and treatments, stress, reduced growth, i.e. the costs associated with deviations from optimal growth conditions. However, deviations from optimal production can have many causes, and it will be difficult to quantify biological costs from diseases or lice alone. More advanced models can be used to separate disease costs from lice costs, but this introduces measurement errors. Alternatively, one can analyze at a more aggregated level, but then one cannot say anything specific about lice costs vs. other sources. What are referred to as biological costs in this report are really inefficiencies, i.e. lower productivity compared to the companies that are the most efficient in the industry. Figure 16 illustrates this principle. The x-axis is the level of an input factor and the y-axis is the output created. The curve shows the relationship between effort and production. The chart is rising, which shows that increased input results in higher output, but output growth slows with increasing effort, which means that further increases in output become more difficult and difficult.

We can use feed and production as a simplified example. Let's say company A uses feed (feed effort) equal to the vertical dotted line in the figure, and produces an amount of salmon indicated by point A. Point AO is the production that the best companies manage to produce given the same amount of feed. Since company A uses the amount of feed less efficiently than the best companies, it will then have a higher eFCR than what the best companies can achieve. The difference between points AO and A is a measure of inefficiency and will be captured in the differences between the company's eFCR and eFCR for the best companies.

Similar analyses can also be performed for the relationship between other input factors (capital, permits, labour input, etc.) and production. Since production is dependent on several input factors used simultaneously, more advanced techniques (Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA)) must be used to measure overall productivity and inefficiency, but this is outside the scope of this report.[42]

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[42] See e.g. Asche et al. (2008); Asche et al. (2009); Vassdal and Holst (2011); Asche et al. (2013); Asche and Roll (2013); Roll (2019) and Asche et al. (2022) for analyses of productivity and inefficiencies in the Norwegian aquaculture industry.

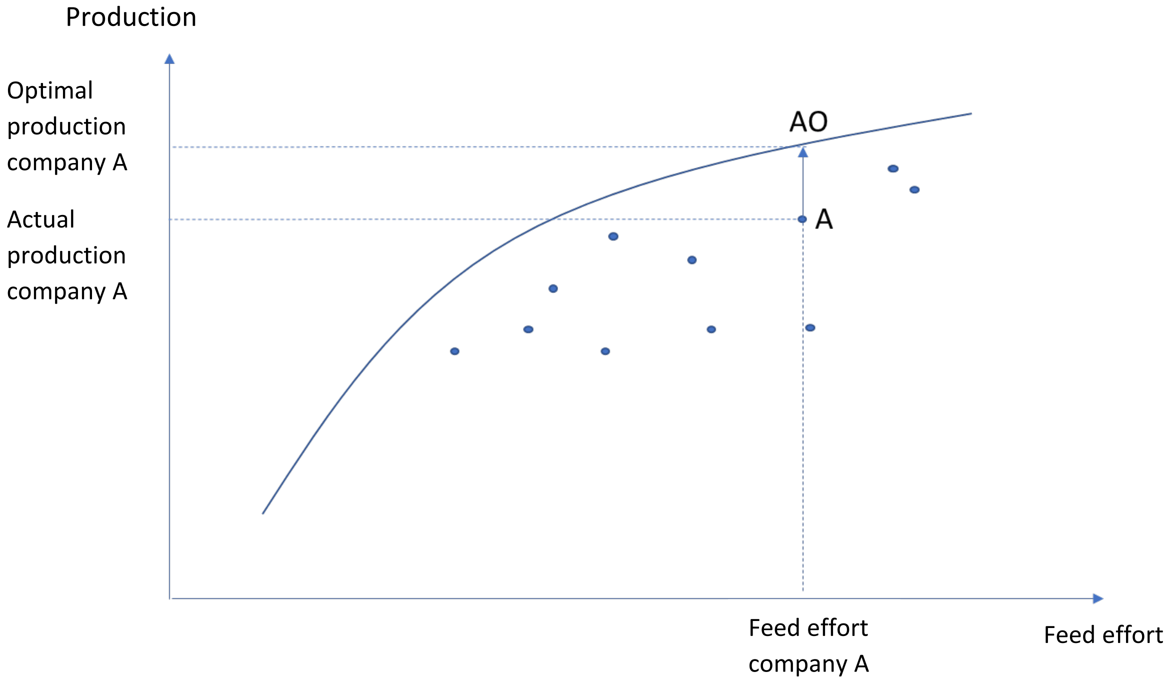

Figure 16. Inefficiency.

3.2. Feed conversion rate as a measure of biological costs

The level of bFCR will be affected by the extent of biological risks, and reported bFCRs will therefore not be a good measure of how efficiently the feed is utilized by the fish in an ideal or optimal operating situation without diseases, lice, etc. An optimal or ideal biological FCR requires that feed utilisation is measured in a production setting *without* biological risk, i.e. if the costs of biological risk are to be calculated, a feed conversion rate measure calculated under optimal or ideal conditions must be used. This report therefore introduces a third feed conversion rate concept – *ideal feed conversion rate* (iFCR). This is a measure of how efficiently the fish utilize the feed under ideal or utopian operating conditions, without being affected by disease, stressed or starved in connection with treatments. This approach is in line with the veterinary medical literature on GBADs. In practice, it will be very difficult to achieve an ideal feed conversion rate as a certain level of stress, disease, treatment, etc. is difficult to avoid in an operating situation. However, benchmarking against iFCR provides an opportunity to calculate the cost of biological risk factors at an aggregated level. Isolation of the costs associated with individual diseases, lice infection, etc. is difficult as the clinical disease picture in aquaculture is complex. Lice and treatment of lice can cause the fish to become stressed and thus more susceptible to disease. Furthermore, the fish may have underlying diseases such as CMS (heart ruptures) that can manifest in increased mortality during salmon lice treatments. Is reduced growth or mortality then due to a disease or is it due to lice treatment? Disease, stress, etc. will reduce growth and can lead to mortality, and will increase eFCR. So will starvation in connection with treatments of the fish. Costs related to deviations from iFCR will then be a measure of costs from biological risk at an overall level. But it will be a imprecise measure of biological costs, contain measurement errors and sensitive to the assumptions made. The sources of inefficient use of feed can be several, not only biological risk, but also feed waste (uneaten food), currents at production sites, but also operating routines, knowledge, and experience come into play. High feed waste that is not caused by diseases, lice, etc. are not biological costs. The same applies to feed eaten by cleaner fish or other deviations from the optimum. The difference between eFCR and iFCR would then be a general measure of feed efficiency, not necessarily just disease and other biological risks. But essentially, the difference between eFCR and iFCR will be driven by biological risk, and used in this report.

So how can one calculate iFCR? One way is to look at the most efficient plants. Figure 15 shows the variation in eFCR for the facilities that have reported to the Directorate of Fisheries' annual profitability surveys. From Figure 15, it appears that there are facilities that have an eFCR below 0.8. It is uncertain whether this level is a representative measure of iFCR, or whether the low figures are due to measurement errors or have other explanations. Informants in industry, analysts and researchers doubt that eFCR of 0.8 is real over an entire production cycle in practice.

It is difficult to find figures on FCR over the entire cycle from smolt to slaughter in the research literature. Field or laboratory experiments are often conducted over shorter periods of time (weeks or months), and there are very few studies from longer periods. The literature and information from informants indicate that it is possible to achieve a bFCR of down to 0.70 in the first phase after exposure and down to 0.95–1.00 in the last phase (see also Sveier and Lied, 1998; Folkedal et al. 2022). The information obtained gives the impression that iFCR can be between 0.9 and 1.0 under optimal conditions over an entire production cycle, i.e. from smolt to slaughter size of around 4–5 kilograms. The uncertainty surrounding the level of iFCR indicates that both 0.9 and 1.0 are used in the calculation of biological costs, hereinafter referred to as iFCR0.9 and iFCR1.0. The difference between iFCR0.9 and iFCR1.0 respectively, and eFCR will then only be used to say something about the level of biological challenges and the cost. Table 3 summarises the various feed conversion rate concepts.

The difference between the achieved and a theoretically optimal feed conversion rate will not alone capture all biological costs, only the *indirect costs*. A total biological cost must also include the *direct* fish health costs. Some of these can be found in the collective cost item "other operating costs". The proportion of other operating costs to be included is somewhat unclear. One of the items in "other operating costs" is called "health" and should be included, but there may also be other costs such as maintenance related to cleaner fish etc. that should also be included, but without more detailed information about the composition of other operating costs, it becomes difficult to identify other relevant biology costs. Before 2015, there is no information on the proportion of health costs, so a stencil rule based on historical data must be used. In the years 2015–2020, health costs accounted for 25% of other operating costs.

Table 3. Different feed conversion rate concepts

Type of feed conversion rate	Comment	Level
Utopian/Ideal Feed conversion rate (iFCR)	The feed conversion rate under ideal or utopian operating conditions. No stress, disease, delousing or mortality. Based on live weight.	0.9–1.0
Biological feed conversion rate from lab experiments (bFCR-lab)	The feed conversion rate is adjusted for dead fish and feed waste that have been collected and weighed. Based on live weight.	0.95–1.0
Biological feed conversion rate from field/commercial operations (bFCR field)	The feed conversion rate is adjusted for dead fish and other wastage. Not adjusted for feed waste. Based on live weight.	1.0–>
Economical feed conversion rate live weight (eFCR)	Based on harvested fish (in gutted weight) and feed quantity. Conversion factor of 1,215 from gutted to live weight.	1.1–>
Economic feed conversion rate whole fish weight (eFCR)	Based on harvested fish (in gutted weight) and feed quantity. Conversion factor of 1,125 from gutted to live weight.	1.2–>
Economical feed conversion rate gutted weight (eFCR)	Based on harvested fish (in gutted weight) and feed quantity.	1.3–>
Feed conversion efficiency (FCE)	1/FCR	

The method of calculating biological costs is as follows. The point of departure are reported production costs as shown in Table 4, which includes capital costs. Then an ideal production quantity is calculated, i.e. the production one should have achieved given feed quantity, by dividing the amount of feed by iFCR. In 2020, an average company used 21,924 tonnes of feed producing 16,609 tonnes of salmon (whole fish weight) and trout (eFCR = 1.32). If the average company had achieved an eFCR = iFCR0.9 then the production would have been 21,924 tons of feed / 0.9 = 24,360 tons of salmon and trout (whole fish weight). Then all the cost elements (with the exception of the harvest cost) are divided by the ideal production converted to gutted weight (Table 3, column 3). The harvest cost remains the same since it only applies to harvested fish. The *indirect biological* costs are then estimated as the difference between the total production costs (i.e. the Directorate of Fisheries' calculations plus cost of capital) and the sum of the costs divided by the ideal production. Finally, the *direct biological* costs are estimated as 25% of other operating costs. Total biological costs then become the sum of the direct and indirect biological costs.

An implicit assumption is made that all costs except feed and harvest/packing are fixed. This will be correct for several of the cost elements such as smolt, depreciation and capital costs, but it will not be as correct to assume for others of the costs as wages, transport and variable costs that are included in the total "other" operating costs. This can be a source of measurement errors, and will give an overestimation of the "biological" costs. At the same time, little is known about the distribution of different types of costs into "other" operating costs, and it is unknown whether the "health" component contains all costs related to biological risk.

Table 4. Production cost 2020 for an average company with and without adjustment for biological costs.

NOK/kg	Average Company	Optimum production (iFCR0.9)	Optimal production (iFCR1.0)
Production (round weight)	**16,609**	**24,360**	**21,924**
Production (gutted weight)	**14,765**	**21,656**	**19,490**
Feed conversion rate	**1.23**	**0.90**	**1.00**
Smolt cost	4.66	3.18	3.53
Feed cost	18.69	12.75	14.16
Labour costs	3.62	2.47	2.75
Depreciation	2.97	2.03	2.25
Other operating expenses	11.11	6.71	6.71
"Biological costs"	0	16.72	13.79
Operating costs in the sea phase	**41.06**	**43.84**	**43.84**
Cost of capital	8.75	5.97	6.63
Production cost in the sea phase	**49.81**	**49.81**	**49.81**
Harvest cost	4.55	4.55	4.55
Production cost	**54.36**	**54.36**	**54.36**

Using this calculation method, biological costs becomes one of the largest cost items, and with an iFCR of 0.9, biological risk was the largest cost item in 2020. Using different levels of the ideal feed conversion rate, the biological costs in 2020 were estimated at NOK 13.8–16.7/kg gutted. One can multiply these costs by an estimate of production, but the amount will be uncertain, and it is therefore not done here. Such an estimate of aggregate costs will be somewhat higher than other calculations (e.g. Iversen et al., 2017; Abolofia et al., 2017, Vedeler, 2017, and Asche et al., 2022), but unlike the other studies, the estimate is an aggregated measure of the total biological costs, including lice, disease and other costs related to biological risk. Rødseth (2016) used a similar method but used a benchmark bFCR of 1.13 from the year 2012, which in isolation will be a lower value compared to ideal feed conversion rates. In addition, Rødseth (2016) added the value of lost profits and estimated a total loss of NOK 7–8 billion for the year 2015. This report does not include lost profits. Firstly, this is not an easy exercise since increased production will, in isolation, result in lower salmon prices. Secondly, it is not certain that increased production would be possible within the current MAB regulations. Many fish farmers are already producing close to the MAB limits. It may therefore be potentially challenging to realise the hypothetical increase in production.

The measurement errors in the method mean that not the entire amount based on iFCR0.9 can be attributed biological risk, but there is reason to believe that the purely biological costs will dominate the other effects. Despite the weaknesses of the method, it will nevertheless provide useful information on developments in biological risk over time, between companies and production areas.

3.3. Development over time

Figure 17 shows a significant increase in "biological costs" after 2005, and is the cost item that has had the largest increase over time. "Biological costs" increased between 2005 and 2010, fell towards 2012 and have increased fivefold between 2012 and 2020. Some of this development can also be seen in mortality statistics. Mortality was high in 2009 and 2010, fell towards 2012, but has since risen. But mortality in 2020 measured as a percentage is lower than in 2010, so increased mortality is not the whole explanation. We will see later that there has been a *significant increase in the weight of dead fish* since 2010–2012. The next chapter will discuss the reasons for the increased biological costs in more detail.

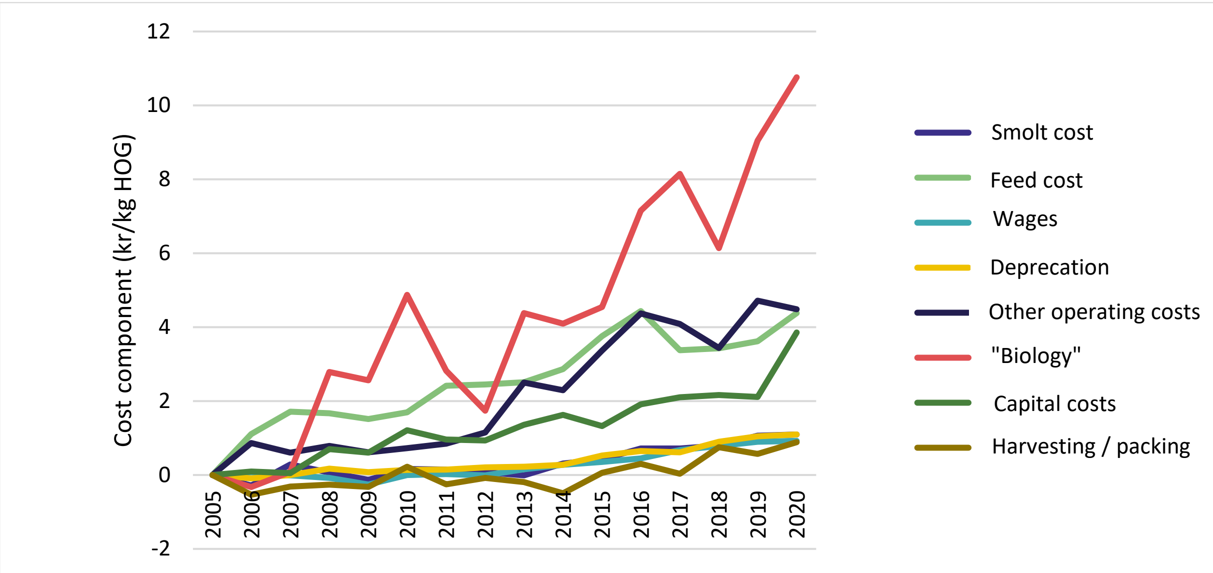

Figure 17. Biological costs over time. (iFCR0.9). For the period 2015–2020, health costs are included as reported by the Directorate of Fisheries, while figures before 2015 indirect biological costs are estimated as 25 % of other operating costs.

The size of the biological costs will depend on the assumptions of iFCR (Figure 17).

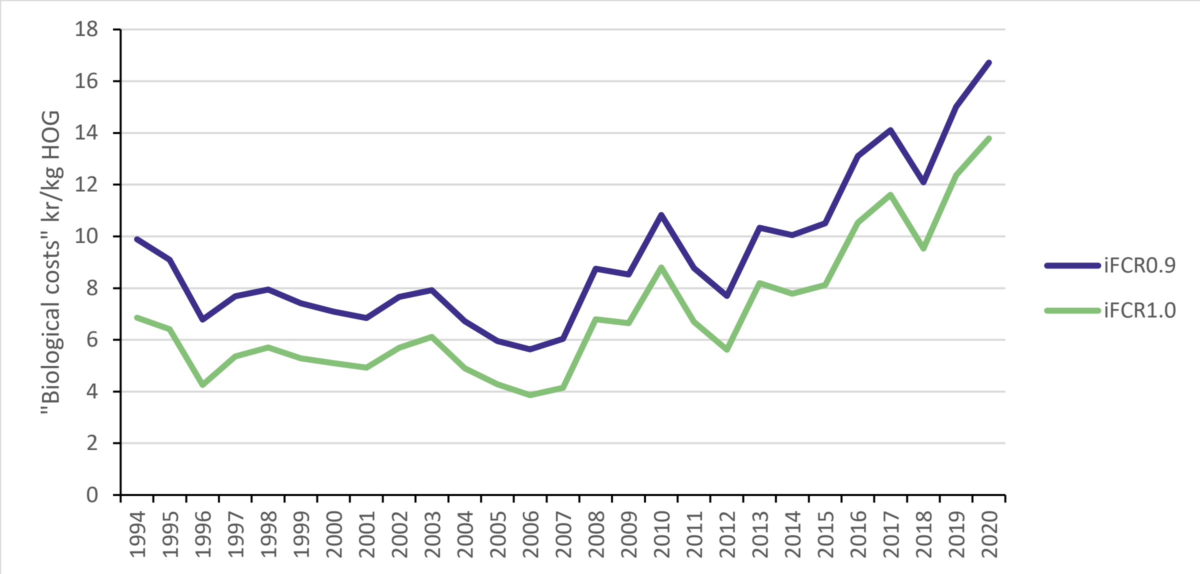

Figure 17. Biological costs. iFCR0.9 vs iFCR1.0

The increase in feed costs between 2005 and 2020 was NOK 7.26/kg not adjusted for biological costs (see Table 2) and falls to approximately NOK 4/kg when costs are adjusted for biological risk. Given the marginal increase in feed prices measured in USD between 2005 and 2020 (see Figure 14), most of the increased feed costs will be due to a depreciation of the krone and increased biological costs. The most important cost to fish farmers, the feed, is driven by both market risk in the form of currency risk and commodity price risk, and by biological risk.

3.4. Production cost composition adjusted for biological risk

Isolating the biological cost enables a more precise analysis of the other cost items. Biological costs have increased their share of total production costs (Figures 18 and 19), and feed costs are no longer the cost element that has increased the most, but have reduced their share of the total by 10 percentage points. The share of the traditionally most important cost components such as feed, smolt and wages has decreased over time. In 2005, they represented almost half of the costs compared to about a third today. The sources of the production cost increase are mainly biological risk, other operating costs and the cost of capital. In the traditional statement of production costs, two of these factors are not included, namely biological costs and capital costs.

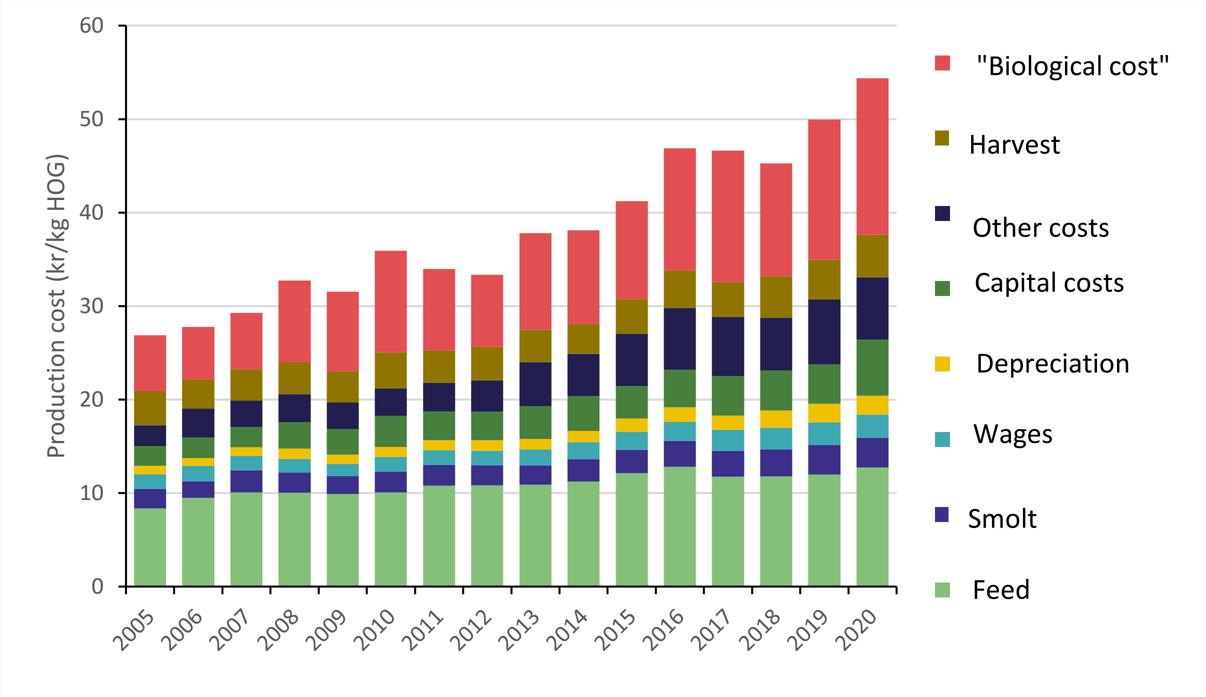

Figure 18. Adjusted production costs.

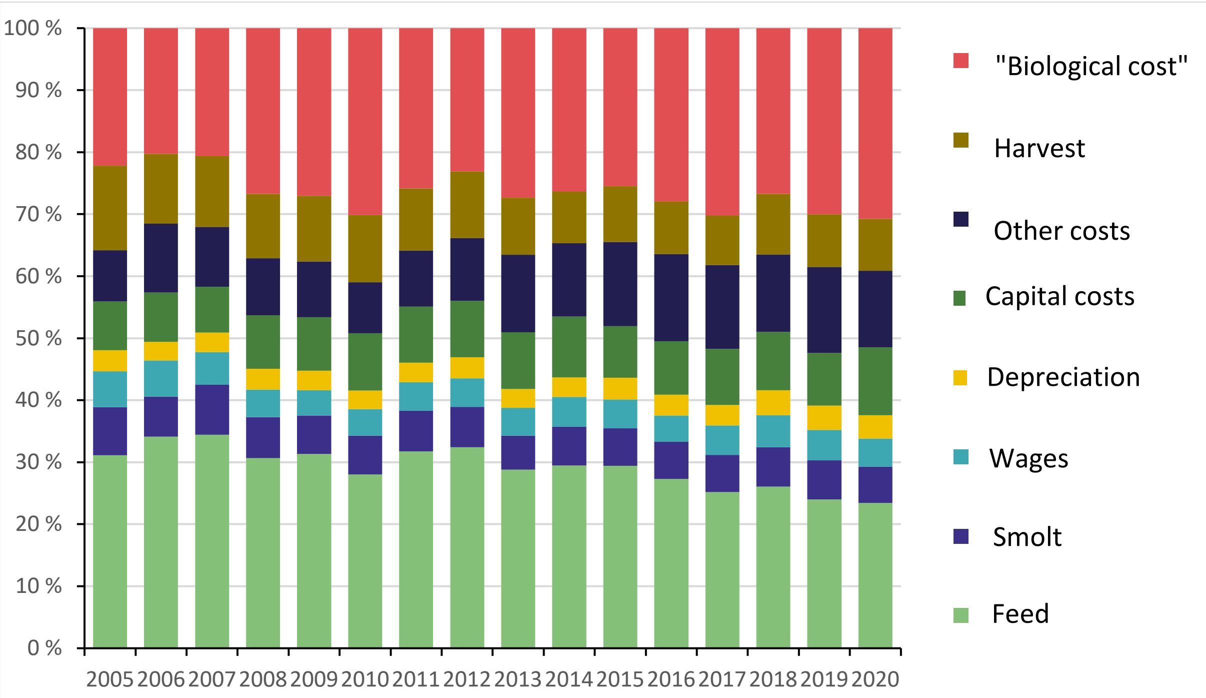

Figure 19. Development of cost composition

3.5. Regional differences

There are significant regional differences in mortality, diseases and lice challenges, which may result in differences in biological costs. The traditional way of presenting costs complicates a comparison of the cost elements by leaving out the impact of sea lice, diseases etc. (Table 5). In 2020, the feed cost in Agder and Rogaland was NOK 21.28/kg, while it was NOK 17.62 in Nordland, but what is the reason for the differences? There are also large regional differences in the other cost elements. Large differences in eFCR between counties are an indication that different biological risks may be an important cause.

Table 5. Traditional manufacture of production costs. Fixed 2020 nok.

NOK/kg	Agder and Rogaland	Western Norway	Trondelag	Nordland	Troms and Finnmark
Feed conversion rate	**1.52**	**1.42**	**1.40**	**1.19**	**1.34**
Smolt cost	6.91	6.33	5.31	4.22	5.57
Feed cost	21.28	19.27	20.08	17.62	19.72
Labour costs	3.23	3.84	4.39	2.92	3.78
Depreciation	2.65	2.60	4.37	3.07	3.19
Other operating expenses	11.01	12.93	9.90	11.15	11.37
"Biological costs"	0	0	0	0	0
Operating costs in the sea phase	**45.07**	**44.97**	**44.04**	**39.00**	**43.63**
Capital*	9.61	9.59	9.39	8.31	9.30
Production cost sea phase	**54.68**	**54.56**	**53.43**	**47.31**	**52.93**
Harvest	5.25	4.79	4.49	4.28	4.79
Production cost	**59.93**	**59.35**	**57.92**	**51.59**	**57.72**

* The cost of capital is based on the national average, but adjusted for regional feed conversion rate.

In the next two tables, the biological cost is subtracted using iFCR0.9 (Table 6) and iFCR1.0 (Table 7). The method is somewhat more difficult for the counties than for the country as a whole since the cost of capital per region is lacking. The average cost of capital for the entire Norway is therefore used but adjusted up or down according to the regional feed conversion rate.

Table 6. Production costs per region 2020, adjusted for "biological costs" (iFCR = 0.9).

NOK/kg	Agder and Rogaland	Western Norway	Trondelag	Nordland	Troms and Finnmark
Feed conversion rate	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**
Smolt cost	4.09	4.01	3.41	3.19	3.74
Feed cost	12.60	12.21	12.91	13.33	13.24
Labour costs	1.91	2.43	2.82	2.22	2.54
Depreciation	1.57	1.65	2.81	2.32	2.14
Other operating expenses	4.90	6.18	4.80	6.36	5.77
"Biological costs"	23.92	22.00	20.64	13.60	19.25
Operating costs in the sea phase	**48.99**	**48.48**	**47.40**	**41.02**	**46.69**
Capital*	5.69	6.08	6.03	6.29	6.25
Production cost sea phase	**54.68**	**54.56**	**53.43**	**47.31**	**52.93**
Harvest cost	5.25	4.79	4.49	4.28	4.79
Production cost	**59.93**	**59.35**	**57.92**	**51.59**	**57.72**

* The cost of capital is based on the national average but adjusted for regional feed conversion rate.

When biological costs are extracted, regional differences in the other cost elements such as smolt, feed, harvest and depreciation are significantly lower than when biological risk is not separated. In Table 2, the smolt cost varies by NOK 2.69/kg, while in Table 6 the difference is NOK 0.90/kg between the regions with the highest and lowest smolt costs. The reduction in variation also applies to the other cost items. The variation in feed costs falls from NOK 3.66 per kg (Table 6) to less than a third. This means that adjusted for differences in feed conversion rate, cost differences between regions will fall dramatically, which in turn indicates that differences in production costs in different counties are mainly due to differences in biological risk. The same effect is seen in Table 7, but the effect is naturally somewhat lower.

Table 7. Production costs per region 2020, adjusted for "biological costs" (iFCR = 1.0).

NOK/kg	Agder and Rogaland	Western Norway	Trondelag	Nordland	Troms and Finnmark
Feed conversion rate	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Smolt cost	4.54	4.46	3.79	3.55	4.16
Feed cost	14.00	13.57	14.34	14.81	14.72
Labour costs	2.12	2.70	3.14	2.47	2.82
Depreciation	1.74	2.83	3.12	2.58	2.38
Other operating expenses	4.90	6.18	4.80	6.36	5.77
'Biological costs'	21.05	19.07	17.53	10.56	16.15
Operating costs in the sea phase	**48.36**	**47.81**	**46.72**	**40.32**	**45.99**
Capital*	6.32	6.75	6.71	6.99	6.94
Production cost sea phase	**54.68**	**54.56**	**53.43**	**47.31**	**52.93**
Harvest costs	5.25	4.79	4.49	4.28	4.79
Production cost	**59.93**	**59.35**	**57.92**	**51.59**	**57.72**

* The cost of capital is based on the national average but adjusted for regional feed conversion rate.

Since 2005, biological costs have increased in all counties (Figure 20), mostly in Rogaland/Agder and Vestland, and least in Nordland. For some counties, there is considerable variation from year to year. This may be due to measurement errors as a result of few observations in some counties. Møre og Romsdal is not included since there are very few locally owned companies in this county. In Rogaland/Agder there are large year to year fluctuations and one possible reason may be companies that participate in joint area cooperation (e.g. zone cooperation).

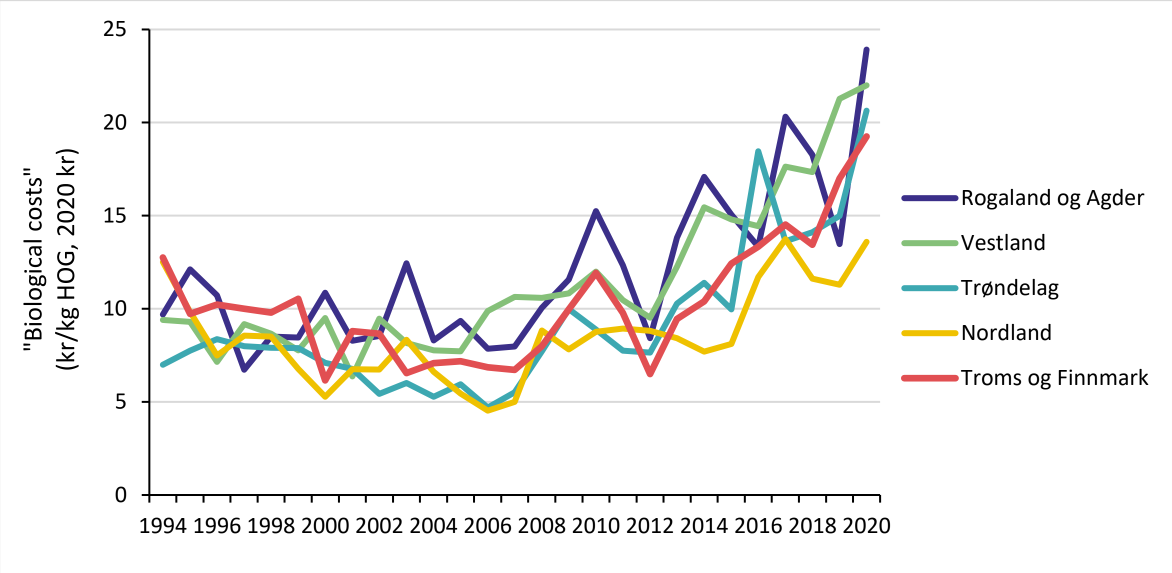

Figure 20. Biological costs per county for the period 1996–2020 (iFCR0.9). Fixed 2020-nok. Source: own calculations based on data from the Directorate of Fisheries' profitability survey.

In addition, disease epidemics will come and go. In Vestland county, there has been a large and prolonged PD outbreak that peaked in 2019, but has declined somewhat in later years. In Northern Norway, ISA has been a major problem. These diseases have also had some outbreaks in the other counties, but some counties have had greater problems than others. There are also regional and site differences in lice infection. In addition, differences in lice problems can also be explained by different operating routines, company strategies and the use of technology.[43]

3.6. Big vs small companies

The Directorate of Fisheries also reports costs for different size groups of companies (Table 8), but it is difficult to identify differences due to size. Studies also show that the small companies have often had the highest profitability (Asche et al., 2018). The companies in Group 1 (1–9 permits) have an average turnover of NOK 250 million/year, so even the smallest category is relatively large. According to EU legislation and definitions, the limit for being defined as small and medium-sized enterprises is an annual turnover of 50 MEUR (~100 MNOK) and fewer than 250 employees. Although the number of full-time equivalents in Group 1 is ~18, the turnover is only half of the turnover that would imply that it is defined as a large company. A fish farming company with 1 permit may have a turnover of around 60 MNOK/year, while a company with 9 permits will have a turnover of around 560 MNOK/year (with a production (round weight) of 1.5 times MAB and a salmon price of NOK 60/kg gutted weight).

[43] See figures here: https://www.barentswatch.no/havbruk/sykdom

Table 8. Adjusted production costs. Different size groups. Group 1 = 1-9 permissions, Group 2 = 10-19 permissions, Group 3 = 20+ permissions.

NOK/kg	Average Company (iFCR0.9)	Group 1 (iFCR0.9)	Group 2 (iFCR1.0)	Group 3 (iFCR1.0)
Smolt cost	3.18	4.10	3.37	2.89
Feed cost	12.75	13.03	12.53	12.64
Labour costs	2.47	2.22	2.04	2.59
Depreciation	2.03	1.79	1.67	2.13
Other operating expenses	6.71	8.13	7.74	6.15
"Biological costs"	16.72	15.45	20.03	16.83
Operating costs in the sea phase	**43.84**	**44.72**	**47.38**	**43.22**
Cost of capital	5.97	5.43	4.66	6.42
Production cost in the sea phase	**49.81**	**50.16**	**52.04**	**49.65**
Harvest cost	4.55	4.15	4.48	4.67
Production cost	**54.36**	**54.31**	**56.53**	**54.32**

4. Reasons for increased biological costs

As mentioned, there may be several reasons for increased biological costs after 2010. Below is a summary of the factors identified as most important.

1. **Higher prices for factor inputs.** A high eFCR means that feed has been used that has not resulted in harvested production. When the price of the feed increases, either through an increase in the price of feed components or a depreciation of the krone, the cost of less efficient use of the feed will be more expensive than before. This effect also applies to other input factors. Higher prices for input factors amplify the negative effect of less efficient use of input factors.

2. **Stricter regulations.** In 1998, requirements for lice counting and delousing were introduced. Since then, the lice limits have been reduced several times (see Figure 5). In 2013, very strict lice limits were introduced (0.2 spring and 0.5 the rest of the year). In the period 2013–2016, the number of delousings rose by 60 per cent. In addition, there was a paradigm shift in delousing methods (see next point). In 2017, the traffic light system was introduced, which increased the focus on salmon lice in aquaculture, and provides financial incentives to keep lice levels in the facilities down. Calculations made by researchers at Institute of Marine Research (IMR) indicate that the number of mature female lice on farmed salmon in a red PO must be below 0.03 before the infection pressure on the wild salmon smolt becomes so low that the PO can be colored green (Sandvik et al., 2021). Attempts to achieving an even lower lice count than today will put further pressure on costs and fish welfare.

   Stricter lice limits, in addition to other regulations such as TLS, have resulted in a significant decline in the number of mature female lice per farmed fish and in the variation in the number of lice per locality (Figure 21). The decline in the variation in the number of lice per locality has been greatest for the POs that initially had the highest lice numbers (Figure 22). The number of sites exceeding the lice limits has fallen over the past 10 years, and the decline has been greatest in Vestland county (Figure 23).

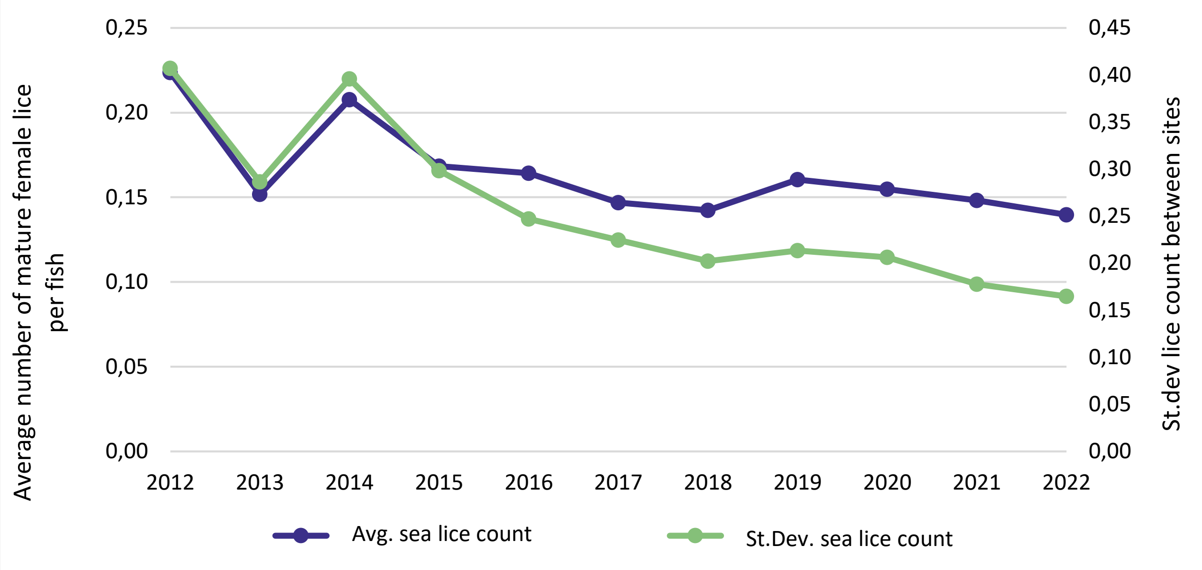

Figure 21. Annual average of weekly number of mature female lice per site, and standard deviation (Stdav) in weekly number of mature female lice per site. Source: own calculations based on data from Barentswatch.

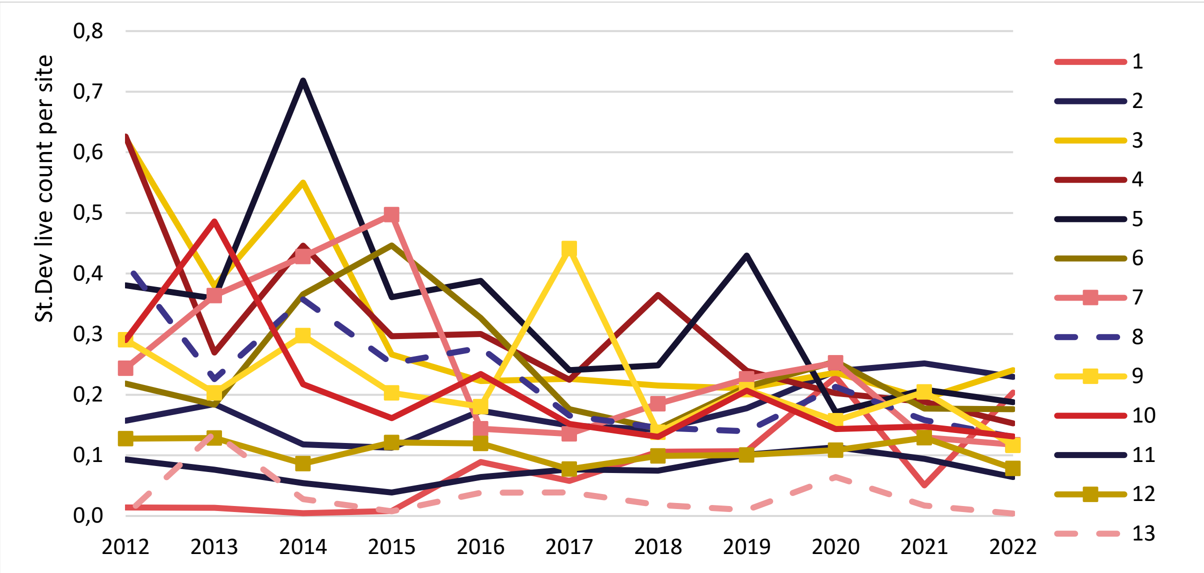

Figure 22. Standard deviation in the weekly number of mature female lice per site for the production areas (1–13). Source: own calculations based on data from Barentswatch.

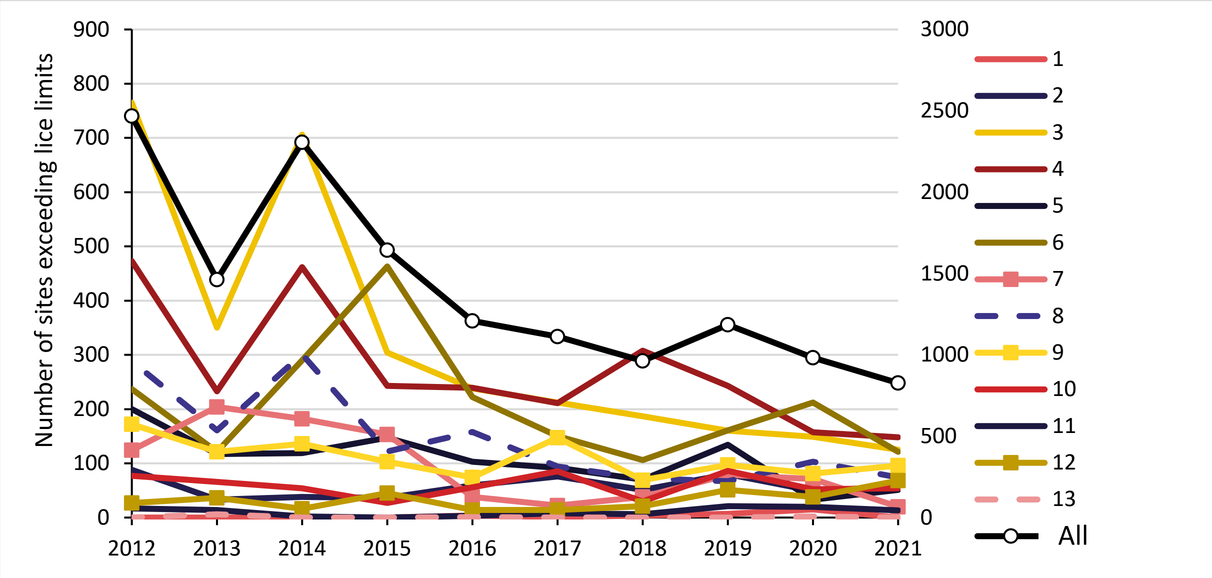

Figure 23. Average number of sites per week that have exceeded lice limits. Source: own calculations based on data from Barentswatch.

The trend is clear, stricter lice regulations have resulted in) a decline in the number of lice, ii) fewer exceedances of lice limits, and iii) less variation in the number of lice between the sites, and iv) less variation in the number of lice on farmed salmon between green, red and yellow PA's. Fish farmers have adapted to stricter lice regulations, and the number of lice per fish has become more homogeneous across sites and also between production areas.

3. **Increased use of non-medicinal delousing methods.** In the period up to 2013–2015, the number of treatments with medicinal delousing agents increased sharply (Figure 24), but as a result of the development of resistance in salmon lice in the same period, efficiency fell and fish farmers had to quickly find new delousing methods. From 2015, there was a sharp increase in the use of non-medicinal methods such as freshwater, mechanical and thermal delousing (in the figure referred to as "mechanical removal")[44,45]. The use of cleaner fish increased sharply in the same period, and fish farmers also paid steadily higher prices per cleaner fish (Figure 26). It is difficult to calculate the number of treatments per site since around 80[46] % of treatments with mechanical methods are carried out at parts of the sites, not the entire sites (partial delousing).

[44] See Coates et al. 2021a, 2021b, Dempster et al. (2021).
[45] See Barrett et al. (2020a), Bui et al. (2020b, 2022)
[46] Using «Mechanical» methods may have reduced the effectiveness of cleaner fish (Gentry et al. 2020).

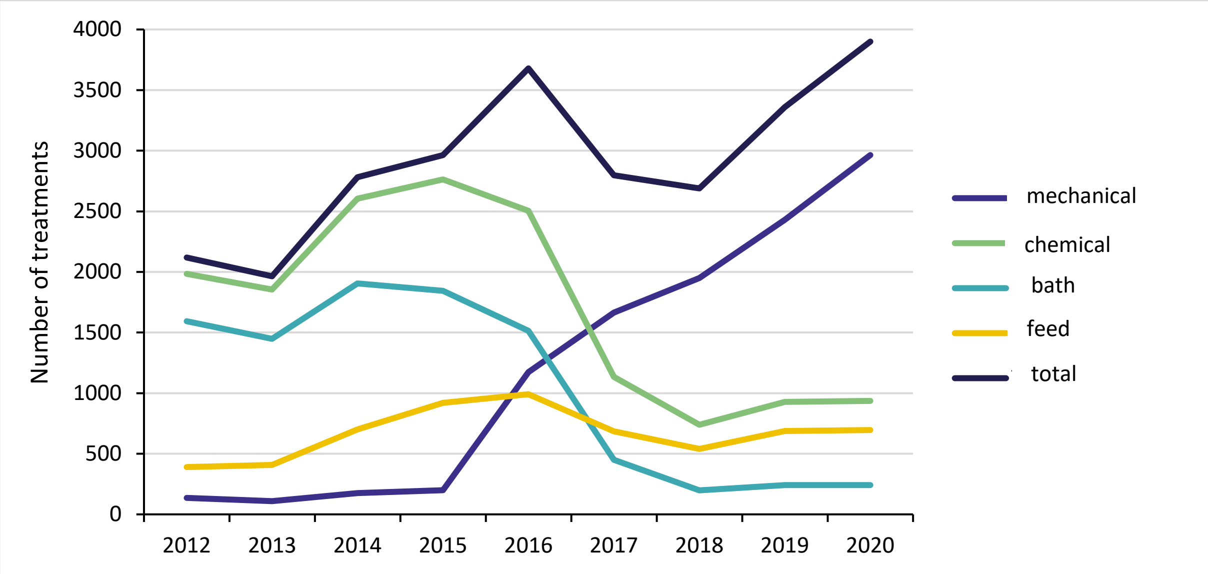

Figure 24. Delousing methods. "Mechanical treatment" is both mechanical, thermal and freshwater treatment. «Drug treatment» is the sum of «bath treatment» and «feed treatment». Source: Barentswatch.

The frequency of mechanical delousing has increased, the proportion of 1–5 delousing per site per year has fallen, while the proportion of 6–15 delousing per site per year has increased (Figure 25).

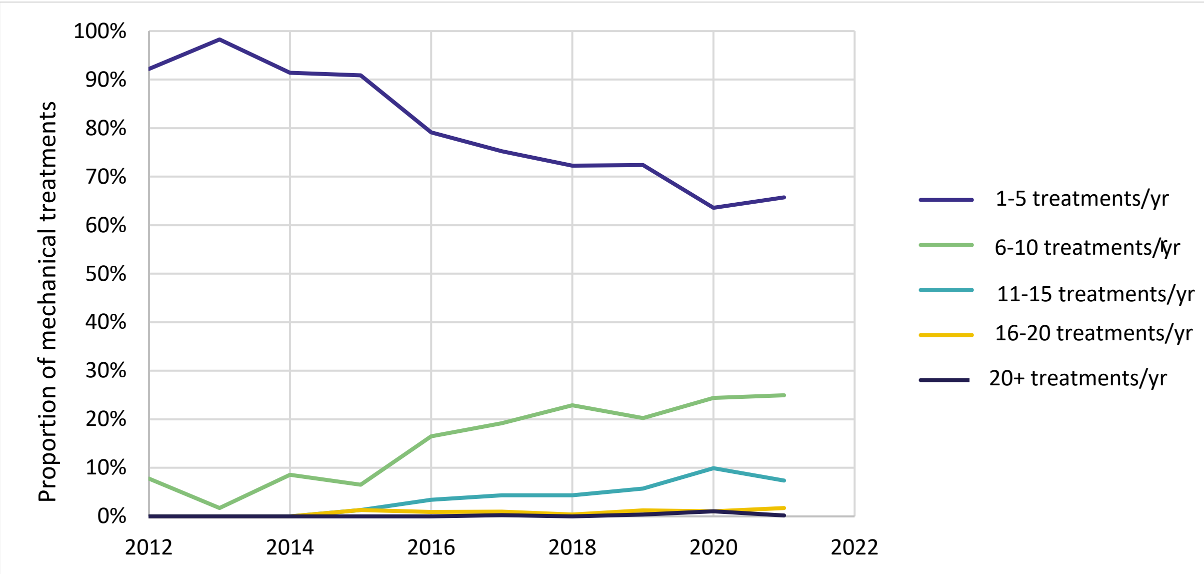

Figure 25. The proportion of groups with the number of mechanical delousings per site per year.

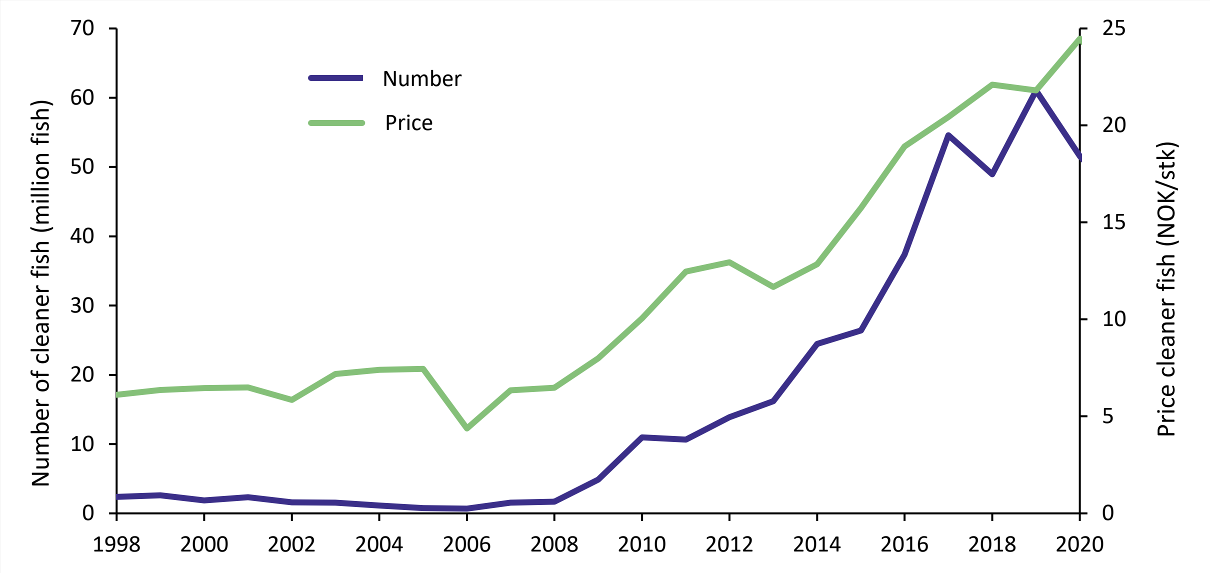

Figure 26. Number of exposed cleaner fish (million fish) and sales price (NOK/pcs). The price is inflation-adjusted (2020 fixed NOK). Source Directorate of Fisheries.

There are regional differences in the delousing rate. The figures below show the frequency of different delousing methods for PA3 and PA4 vs. PA7, PA8 and PA9 (Figure 27). The figures are not directly comparable as there will be differences in the number of sites and quantities produced. Production, in particular, will have changed over time. Since Nordland has green PA's while Vestland has had yellow and red, production will have developed at very different rates, but the regions are probably relatively similar in terms of production. In 2020, 357,393 tonnes of round weight were produced in PA3 and PA4 compared to 397,639 tonnes in PA7, PA8 and PA9. Although both areas have had an increase in delousing frequency, the increase has been greatest in Western Norway. [47] The increase in the use of "mechanical" delousing methods in PA3 and PA4 has increased from 55 in 2012 to 1,233 in 2020, while in PA7, PA8 and PA9 the frequency has increased from 0 to 521. The increase has been more than twice as large in Vestland county than further north.

[47] There are also regional differences in lice pressure on wild salmon.

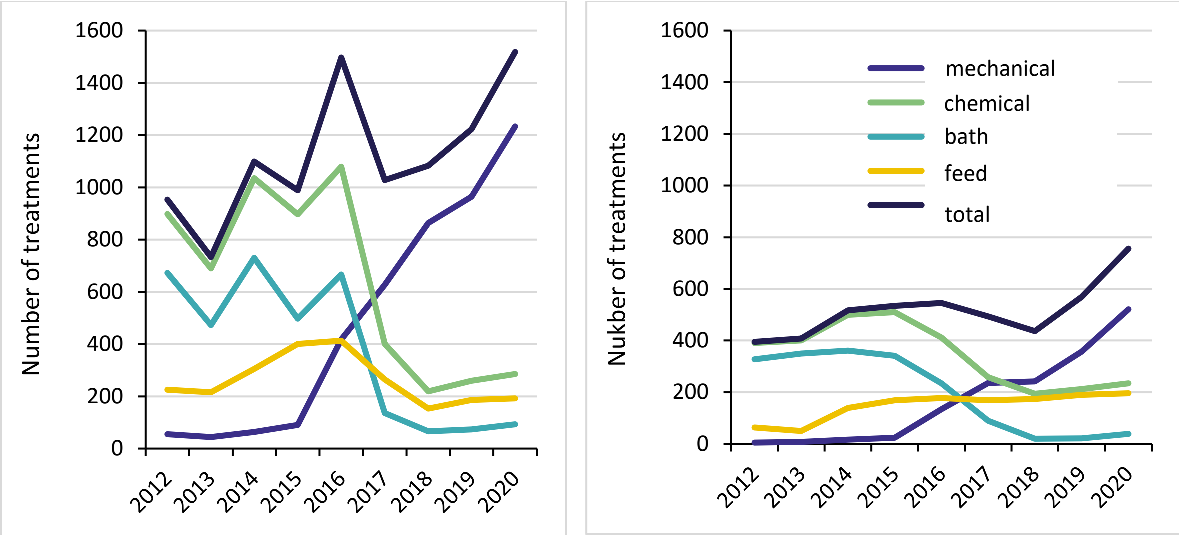

Figure 27. Frequency of delousing methods in PA3 and PA4 (covers Vestland county) and PA7, PA8 and PA9 (covers most of Nordland county). Source: Barentswatch.

4. **Increased weight of dead fish.** [48] The figures below show mortality for the whole country (Figure 28), mortality in other years at sea per region (Figure 29), and average weight of dead fish over time per generation and per region (Figure 30). Although mortality measured as a percentage of the number of fish in the sea has fallen since 2010 (Figure 28, yellow line), mortality from large fish has increased (Figure 28, orange line), while mortality of the smallest fish has decreased (Figure 28, blue line). Increased mortality from large fish is more expensive than small fish since more variable costs have been invested. In addition, the fixed costs are distributed across fewer kilograms.

[48] For more information about the development and causes of mortality in the smolt and ongrowth phase, see Bang Jensen et al. (2020), Bui et al. (2022), Bui et al., (2020b), Gåsnes et al. (2021), Oliveira et al. (2021), Overton et al. (2019a; 2019b), Persson et al. (2022) and Sviland Walde et al., (2021, 2022).

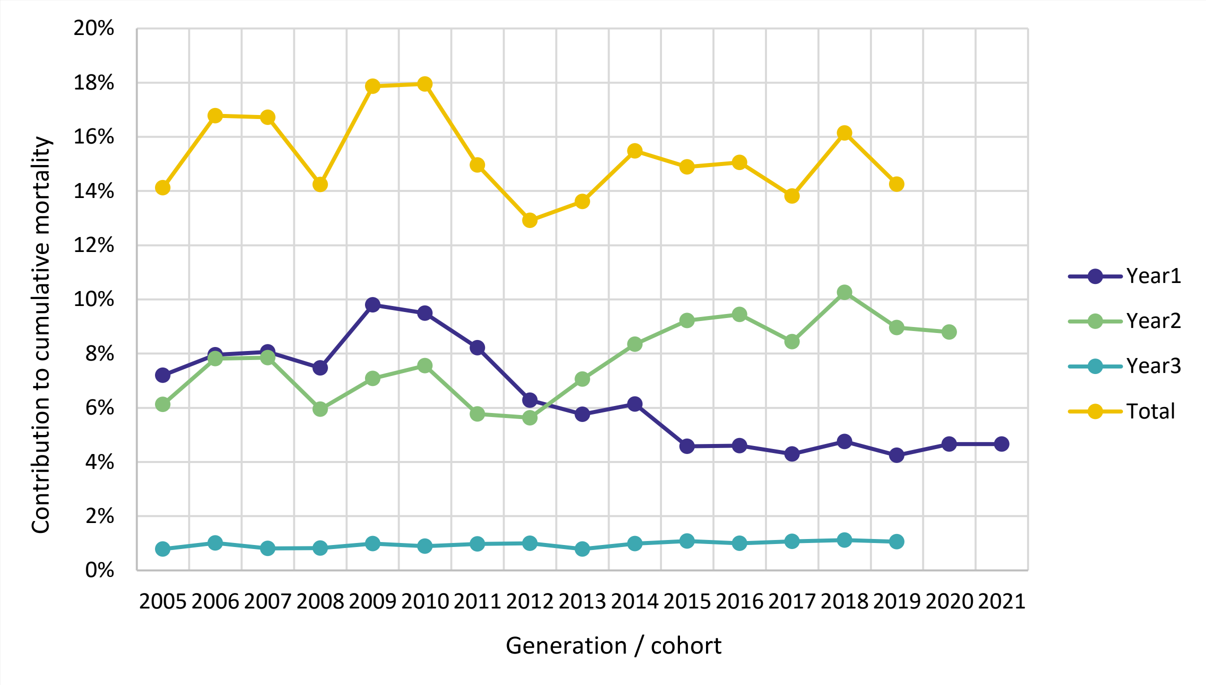

Figure 28. Mortality per generation and number of years in sea. Mortality is calculated as the number of registered dead fish divided by total release per generation. First calendar year in sea = dark blue line, second calendar year in sea = green line, third calendar year in sea = turquoise line, and total mortality = yellow line. Source: own calculations based on the Directorate of Fisheries' biomass statistics.

Mortality of fish in the second year in sea has historically been highest in Vestland county, and lowest in Nordland. Since 13G (fish released in 2013), mortality from large fish has more than doubled in Western Norway. In particular, there has been a sharp increase between 12G and 16G. The increase has also been large in mid-Norway, but not as high as in Western Norway.

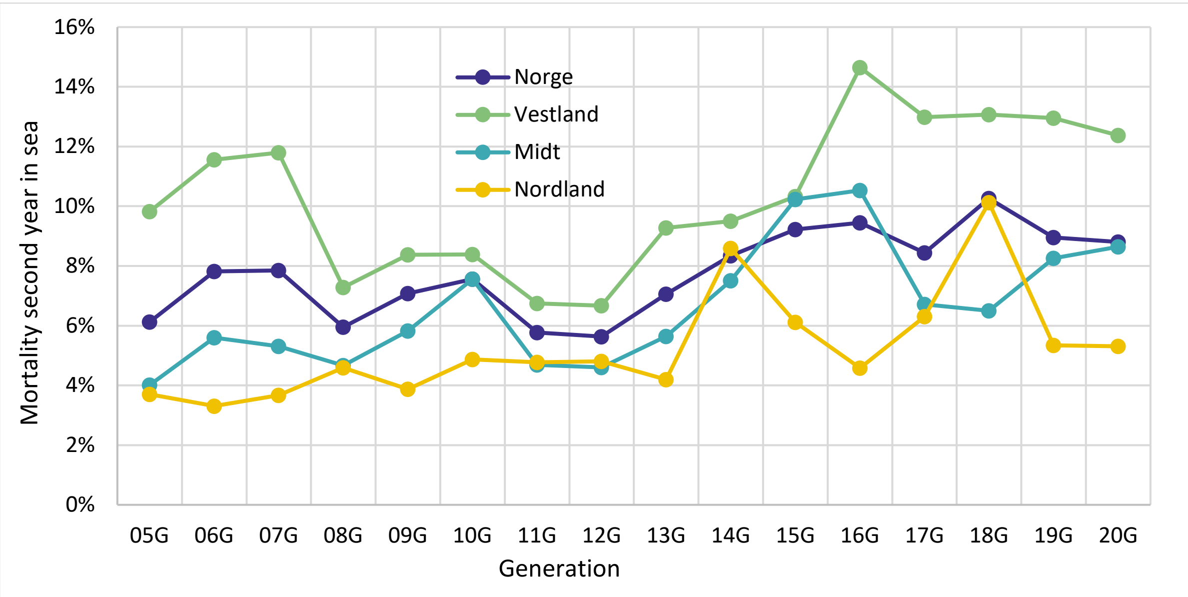

Figure 29. Mortality for fish in the second year at sea, for the country as a whole and in three geographical areas (Vestland, mid-Norway and Nordland). Mortality is calculated as the number of registered dead fish

divided by total release per generation. Source: own calculations based on the Directorate of Fisheries' biomass statistics.

The average weight of dead fish has increased since the 12G cohort (fish released in 2012). In Western Norway, it has increased from 1.5 kg to just under 2.5 kg, an increase of almost 1 kg. The average weight of dead fish has also increased in the other areas. In Nordland, dead fish weight has increased from 1 to almost 2 kilograms. Nationwide, the average weight of dead fish has increased by almost 1 kilogram. Increased dead fish weight combined with increased mortality of large fish is an important driver of increased biological costs. In addition, higher prices for factor inputs increase the price of this source of inefficiency. Financially, this will be expensive as a considerable amount has been invested in producing a fish weighing 2–2.5 kg. The development has motivated increased investments in stun boats that can harvest fish that are weakened in connection with treatments., and which could potentially die and lead to production losses. Potentially, increased use of stun boats could result in reduced dead fish weight in the future. Other factors that can potentially contribute positively to fish welfare are an increased focus on smolt quality. Some researchers and practitioners point to a connection between smolt produced in RAS facilities and increased mortality from large fish, but this is a topic that needs to be researched more before it is possible to conclude since the causes of increased mortality of large fish are complex. However, some studies already show that smolt quality is an important explanatory factor for losses in ongrowth fish production (Pincinato et al, 2021).[49,50]

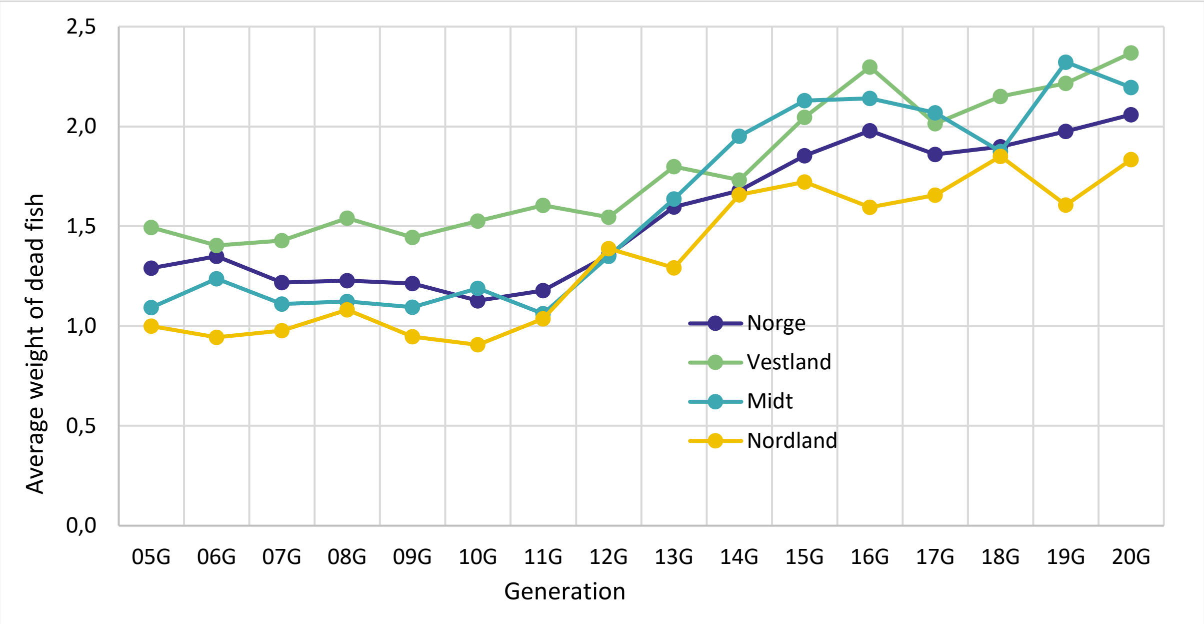

Figure 30. Regional differences in the weight of dead fish in other years at sea. Own calculations based on the Directorate of Fisheries' biomass statistics.

[49] See e.g. Barrett et al. (2022).

[50] See e.g. Frisk et al. (2020) and https://ilaks.no/skjelde-fisken-er-jo-halvdau/, https://ilaks.no/skjelde-vi-har-enda-mer-a-ga-pa/, https://ilaks.no/beitnes-johansen-alt-tyder-pa-at-ras-fisk-er-mindre-robust/.

5. **Decrease in harvest weight.** There was a decrease in harvest weight between 2011 and 2016 of 600 grams (Figure 31). Since then, the average harvest weight has increased slightly (~200g). The largest drop in harvest weight coincides with the challenging period of increased use of "mechanical" delousing methods. One possible explanation is that the fish are harvested instead of being exposed to another round of delousing. In addition, companies operating with production levels that are close to the MAB limits can potentially also be an explanatory factor (often coined "MAB slaughter")[51]. A decline in harvest weight has significant negative consequences for fish farmers' financial performance. First, fixed costs are distributed across fewer kilograms. Furthermore, smaller quantities of fish are harvested and sold, which in isolation results in lower sales revenues, and in addition, the price of smaller fish will be lower than larger fish. 1–2 kg salmon is sold at a discount of approx. NOK 15 per kg on average compared to 4–5 kg salmon.

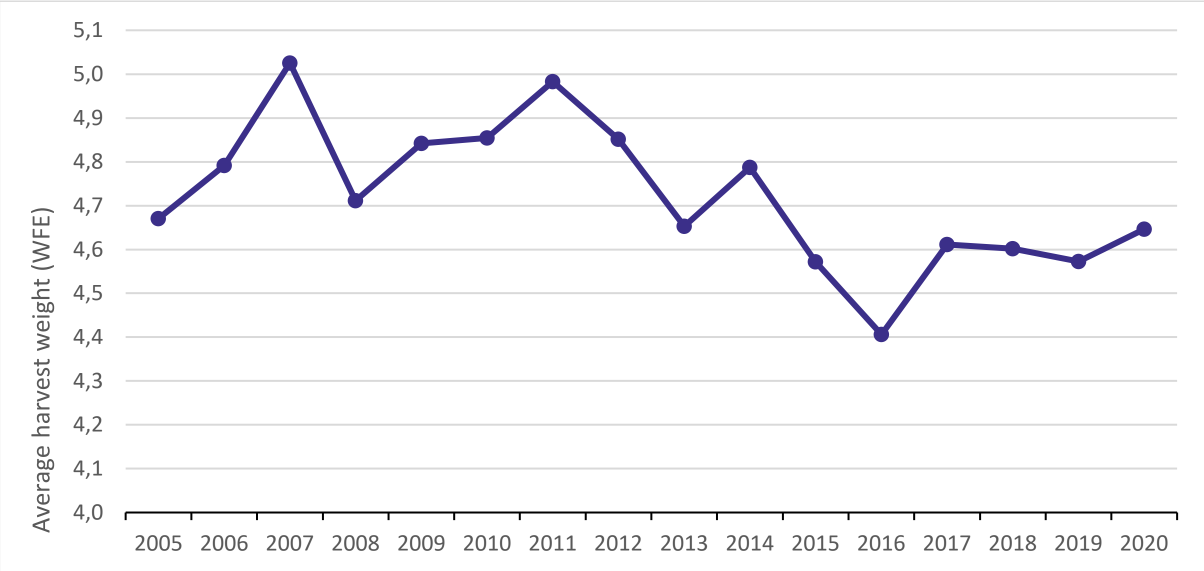

Figure 31. Harvest weight in other years at sea (WFE). Per generation. Source: own calculations based on the Directorate of Fisheries' biomass statistics. Truncated y-axis.

Since 2010, there has been a significant change in time to harvest (Figure 32). In 2010, about half of the fish were harvested in the second year at sea and the rest in the third. This can have several causes, such as the release of larger smolts that live for a shorter time in the sea (shorter production cycle in the sea), forced harvest (and lower harvest weight) and potentially also an increase in spring release instead of autumn release. Iversen et al. (2019) documents that the proportion of spring vs autumn releases has gone from 65:35 in 2005 to 53:47 in 2014[52], so this is probably not an explanation. Larger smolt/shorter production time and increased biological challenges then remain as possible explanatory factors.

[51] https://www.hi.no/hi/nyheter/2022/august/bloggebater-berger-fisk-etter-avlusing. See also Barrett et al. (2022).
[52] Does not mean that the fish is 3 years old when harvested. Fish released in the fall will be just over a year old as it begins its third calendar year at sea.

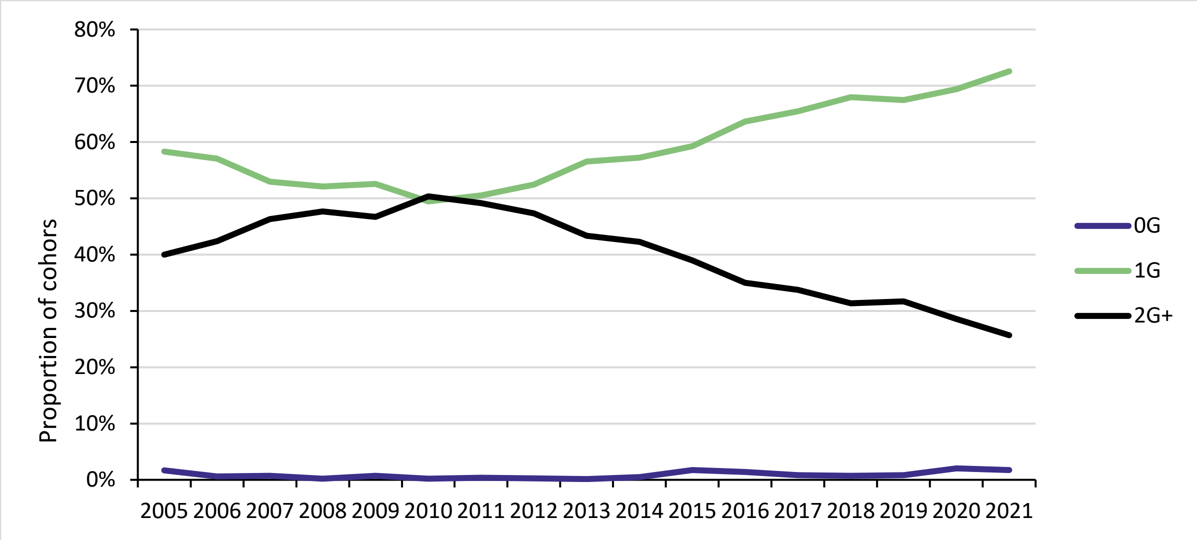

Figure 32. Age at harvest. 0G = same year as release to sea, 1G = second year at sea, and 2G+ is third year at sea or older.

The size of smolt released to sea has increased (Iversen et al. 2017; 2019), but information on average smolt size is not publicly available. However, it is possible to say something about the proportion of post-smolt by looking at the proportion of smolt release consisting of fish above and below 250g. The proportion of large smolt has increased since 2010, and the largest increase has occurred after 2014 (Figure 33).

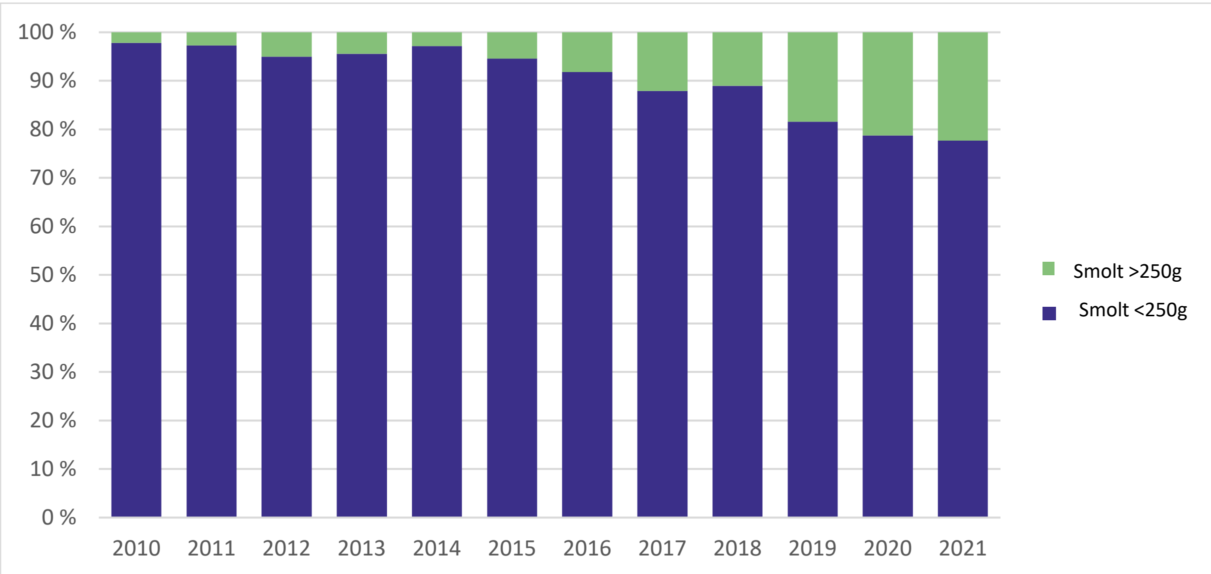

Figure 33. Smolt size. Proportion of smolt released above and below 250 grams. Source: Own calculations based on the Directorate of Fisheries' statistics.

6. **Increased economic feed conversion rate.** The figures above supplemented with other information document increased mortality of large fish, increased dead fish weight, more frequent delousing, increased use of «mechanical» delousing methods, long-term PD/ISA outbreaks. Disease, parasitic infestations, treatments cause stress and reduced growth. Disease does not necessarily cause acute mortality, but can be a long-term chronic disorder with a negative effect on growth and fish welfare. PD is a type of disease that does not

necessarily kill the fish (i.e. acute mortality), but causes the fish to become thinner and less able to utilize the feed. Furthermore, the fish must be starved in connection with treatments. These are all factors that increase the economic feed conversion rate. The feed conversion rate has increased since 2005 and is now above 1.3 compared with 1.2 in 2005, and down to 1.15 in the 1990s (Figure 34).

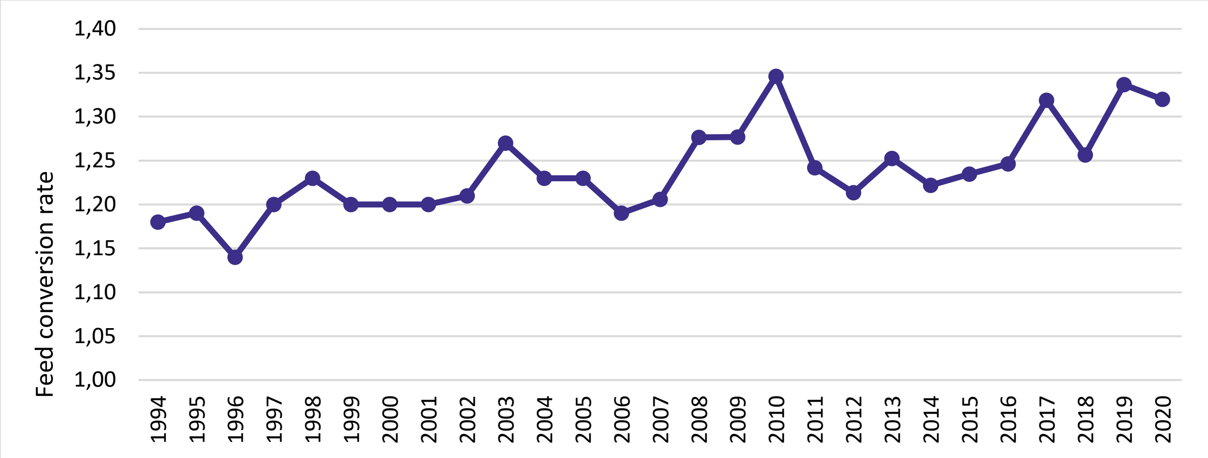

Figure 34. Average economic feed conversion rate (eFCR). Source: Directorate of Fisheries profitability surveys.

There are large geographical differences in feed conversion rate (Figure 35). For fish released in 2020, Vestland county (eFCR = ~1.35) was significantly higher than Nordland (eFCR = ~1.15). Since 11G, the difference between the regions has increased.

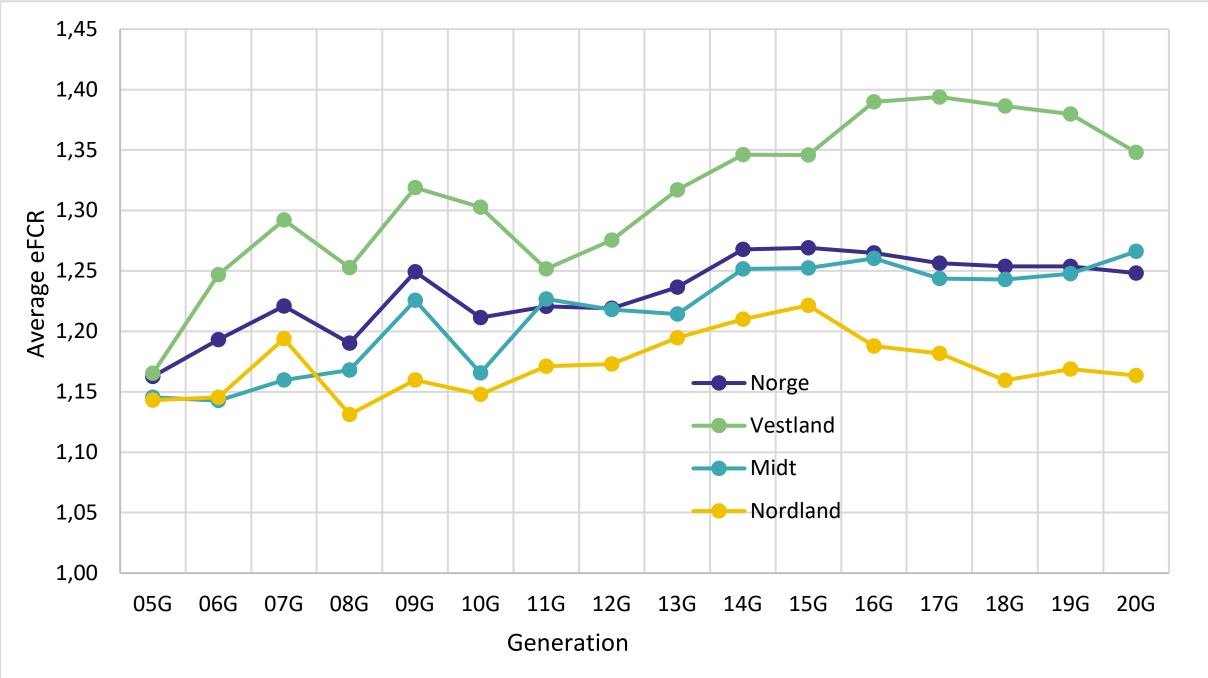

Figure 35. Economic feed conversion rate per generation for a sample of counties. Based on the Directorate of Fisheries' biomass statistics.

5. Conclusion

Production costs in aquaculture have increased 3–4 times faster than inflation in the period 2005–2020, and the increase in costs cannot only be explained by higher prices for factor inputs. The cost explosion has not abated over the past two years. On the contrary, the trend continues and the cost of production including capital is approaching NOK 60 per kilogram gutted weight. The increase in production costs makes it more difficult to maintain the historical profitability than seen in 2016. Several studies have investigated the causes of cost developments and have identified lice, smolt and increased capital intensity as important explanatory factors. "Biological costs" are a type of costs that have received a lot of publicity, but have not been quantified to any great extent. This report calculates the costs from biological risk based on the discrepancy in costs between reported production and an ideal/utopian operating situation. While the ideal feed conversion rate is representative of an optimal/ideal operation of facilities without disease and lice, the economic feed conversion rate will increase with biological risk. The discrepancy between the realised and the ideal feed conversion rate provides us with information on the level of indirect biological costs (e.g. from mortality, reduced growth, starvation, etc.). The direct biological costs are calculated on the basis of information about health costs, and the sum of the indirect and direct costs gives the total biological costs.

The results show that biology costs are one of the largest cost items in salmon farming, and that the level has increased significantly since 2005, and especially since 2012. In 2020, the “biology cost” was estimated to NOK 10–14/kg, compared with a feed cost of approximately NOK 13–14/kg. Of an increase of NOK 27.49/kg gutted weight (in fixed 2020-NOK), biology costs accounted for NOK 9.50–10.76/kg, a 35–40 per cent of the increase, compared with 40–45 per cent for feed, other operating costs and capital. In addition to the cost increase, the variation in production costs has also increased, especially after 2012. The method behind the calculations is simple, and there will be measurement errors that give uncertain estimates. Further research should be done to find methodology that can increase the precision of the estimates.

The reasons for the increase in biological costs are complex but are mainly related to stricter environmental regulations and the fish farmers' response to the restrictions, increased weight of dead fish, in addition to disease outbreaks. In 2013, very strict lice limits were introduced, which led to more frequent delousing, increased drug use and increased release of cleaner fish. Around 2015, the effectiveness of medicinal delousing agents fell, resulting in an abrupt transition to new and untested non-medicinal mechanical methods (including thermal ones), which in turn resulted in reduced fish welfare and health, and increased mortality of large fish. Over the past 10 years, the average dead fish weight has doubled from around 1 to 2 kilograms. The average harvest weight has fallen and the proportion of fish harvested in the first year at sea has increased. The last decade is also characterized by frequent and prolonged outbreaks of PD and ISA. The sum of these factors has increased biological risk and has resulted in increased biology costs and increased economic feed conversion rate.

Stricter environmental regulations in Norway and other production countries have resulted in limited production growth and thus higher salmon and rainbow trout prices. The operating margin has therefore remained at a high level despite the cost increase (although with large variations from year to year). An important question is whether this will last. Increased costs increase risk in the industry, and rising biological costs indicate increased biological risk. The industry is climbing higher and higher up the cost ladder, which increases the susceptibility to disruptive developments, e.g. new technology that does not have the same biological challenges as open cages. The high salmon prices increase the profitability of alternative technologies such as offshore and in semi-closed facilities that combined with increased costs in open cages reduce the relative competitiveness of conventional technology for those companies that have high biological costs.

The analysis also has another important contribution. It shows an increased internalization of negative externalities. Negative externalities is a term economists use to describe costs to society that arise as a result of a company's activities, but which are not borne by the enterprise itself, creating a wedge between corporate and society's costs. Pollution is one such example. The typical textbook example is a factory that pollutes and creates increased costs for other people or businesses. The classic textbook solution is then to impose an environmental tax (Pigouviuan tax) on companies that is set equal to the marginal cost of environmental damage. As a result of the tax, companies' costs will increase with the level of the cost of environmental damage in line with the *polluter pays* principle. In technical terms, this is called an *internalization* of negative externalities. However, the most important externalities in aquaculture such as lice and diseases are poorly covered by such a classic textbook definition. While the effects of sea lice and diseases from salmon farming on wild salmonids are in line with the classic definition of externalities, they do not fully describe the costs to society of salmon lice and fish diseases in aquaculture. The term [53]*spatial externalities* is then more appropriate, describing a situation where businesses pollute each other, and can give rise to the tragedy of the commons. In aquaculture, salmon lice and diseases will spread from plant to facility. This will increase costs for fish farmers in areas with a lot of lice and diseases, and provide a partial internalization of the externalities. Recent research shows that current regulations amplify this effect. The results of the analyses in this report show that society's costs from spatial externalities are significant and are largely borne by the farmers themselves. Stricter environmental and fish health regulations, such as lice limits and the traffic light system, have contributed to an internalisation of society's lice and disease costs. Areas with high lice levels (Vestland) also have the highest biological costs, while areas with low lice levels (Nordland) have the lowest biological costs. These findings will have consequences for the choice of regulations and taxation of the aquaculture industry. For example, how effective will an environmental tax on salmon lice on farmed salmon be when fish farmers' lice costs are already high and increase with increased sea lice infection in a geographical area? Furthermore, the results will provide useful information for the optimal design of other taxes, e.g. a resource rent tax. How a resource interest tax will work in an industry where the extraordinary profitability is created by environmental regulations, and the main externalities are partially internalized and of considerable scope, has not

[53] See Asche, F., Eggert, H., Oglend, A., Roheim, C. A., & Smith, M. D. (2022). Aquaculture: Externalities and Policy Options. Review of Environmental Economics and Policy, 16(2), 282–305 and Estay, M., & Stranlund, J. K. (2022). Entry, location, and optimal environmental policies. Resource and Energy Economics, 70, 101326.

been studied in an academic setting. Nor have the environmental consequences of a resource rent tax in aquaculture been assessed.[54,55,56,57]

[54] See Estay, M., & Stranlund, J. K. (2022). Entry, location, and optimal environmental policies. Resource and Energy Economics, 70, 101326.
[55] See Oglend and Soini (2020).
[56] Oglend and Soino (2020) are an exception.
[57] NOU 2019:18 «Taxation of aquaculture» did not examine the environmental consequences of a resource rent tax even though it was part of their mandate but assumed that the current environmental regulations are sufficient (see page 26–27, section 2.3). However, recent research indicates that environmental regulations reinforce the environmental challenges in aquaculture.

6. References

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